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In July 1989 the President submitted to Congress his Administration's proposals for revising the Clean Air Act. One major component of his plan is the Clean Alternative Fuels Program. This program would replace a portion of the motor vehicle fleet in certain cities with new vehicles that meet stringent air emission limits operating on clean burning fuels such as methanol, ethanol, compressed natural gas, liquified petroleum gas, electricity, and reformulate gasoline.

This report, relased by EPA, is the fourth in a series of reports that will discuss the economic and environmental issues associated with each of these fuels.

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April 1990

TABLE OF CONTENTS

Page

Preface

Executive Summary

1.0 Introduction and General Concepts 1

2.0 Properties of Ethanol 8

3.0 Economic Analysis of Ethanol 15

3.1 Domestic Production 15

3.1.1 Fermentation From Grain 15

3.1.1.1 Previous Federal Studies 15
3.1.1.2 Current U.S. Ethanol Production 15
3.1.1.3 Hydrous Versus Anhydrous Ethanol 16
3.1.1.4 Corn and Ethanol Production Economics . 19
3.1.1.5 Tax Subsidies 22

3.1.2 Ethanol Production From Natural Gas and Petroleum 23
3.1.3 Non-Food Biomass 24

3.2 Imports 27

3.3 Transportation and Marketing Costs 30

3.3.1 Delivery to Terminal or Bulk Plant 30
3.3.2 Distribution to Consumers 32

3.4 Vehicle Hardware Costs 34

3.5 Vehicle Operating Costs 36

3.6 Budget Costs of Ethanol 40

4.0 Environmental Analysis of Ethanol 44

4.1 Urban Ozone and PAN Levels 44

4.2 Air Toxics 49

4.2.1 Ethanol 49
4.2.2 Benzene 50
4.2.3 Aldehydes 50
4.2.4 1,3-Butadiene 51
4.2.5 Other Air Toxics 51

(continued on next page)

Table of Contents, Continued

4.3 Global Warming 52

- 4.3.1 Impact of Ethanol from Corn 52
- 4.3.2 Impact of Ethanol from Cellulosic Biomass . . 56

4.4 Agricultural Side Effects on the Environment . . . 57

4.5 Other Environmental and Health/Safety Issues . . . 58

- 4.5.1 Spill Issues 58
- 4.5.2 Leak Issues 60
- 4.5.3 Fire Issues 61
- 4.5.4 Ingestion 62

Appendix A Summaries of Previous U.S. Government Ethanol Studies

Appendix B Review Article on Ethanol from Non-Food Biomass

Appendix C Memo: "Cost Estimate for Ethanol Gasoline-Equivalent Price"

Appendix D Memo: "Ethanol Fueled Vehicles - Experience to Date"

PREFACE

In July 1989 the President submitted to Congress his Administration's proposals for revising the Clean Air Act. One major component of his plan is the Clean Alternative Fuels Program. This program would replace a portion of the motor vehicle fleet in certain cities with new vehicles that meet stringent air emission limits operating on clean burning fuels such as methanol, ethanol, compressed natural gas, liquefied petroleum gas, electricity, and reformulated gasoline.

This report, released by EPA, is one in a series of reports that will discuss the economic and environmental issues associated with each of these fuels. The Environmental Protection Agency will prepare reports on the candidate fuels according to the following schedule.

Fuel	Final Report
Methanol	released September 1989
Compressed Natural Gas	released April 1990
Ethanol	released April 1990
Liquefied Petroleum Gas	to be released later in 1990
Electricity	to be released later in 1990
Reformulated Gasoline	after receipt of formulation

The ordering for these reports does not represent any preference by the Administration, but is the result of the status and availability of the information and research needed to prepare the reports.

The economic and environmental analyses contained in this and the other reports assume the full implementation of the President's Alternative Fuels Program.

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EXECUTIVE SUMMARY

This report discusses aspects of ethanol use as a motor vehicle fuel at high concentrations (e.g., 85%-100%) in place of gasoline. Lower level ethanol mixtures (10% ethanol and 90% gasoline) are already widely used. In fact, about 7.5% of gasoline sold in the United States currently contains ethanol at this level. This represents an annual ethanol production of 840 million gallons.

Ethanol has a number of properties which would make it a good motor vehicle fuel. Its octane is higher than gasoline which, together with other fuel properties, means vehicles could be designed for improved efficiency (about 30% greater). Its vapor pressure is much lower which would result in lower evaporative emissions but would result in increased cold starting difficulty with either 100% hydrous (i.e., ethanol containing 5% water) or anhydrous ethanol. Its flammability is also lower which should help result in decreased number and severity of vehicle fires. Anhydrous ethanol, as currently used in low level blends, would be required to help prevent phase separation if the ethanol is to be used in flexible fueled vehicles where the ethanol fuel could occasionally be mixed with straight gasoline. However, in vehicles dedicated to the use of high level ethanol fuels (e.g., 85%-100% ethanol) it may be possible to use hydrous ethanol, which requires slightly less cost and energy to produce.

About 95% of the fuel ethanol currently used in the United States comes from corn. Corn is converted to ethanol by either the dry-milling or wet-milling processes. The dry-milling process involves milling the grain but not separating its components before the "mashing" process forming ethanol. This process yields distillers dried grains with solubles as a side product which is a common animal feed. The wet-milling process (accounting for about 67% of the ethanol produced) involves separating the corn into its major components. The starch is then converted into ethanol. The by-products from wet-milling are more valuable than those from dry-milling.

Under an expanded fuel ethanol program as considered in this report the wholesale cost range for ethanol produced from corn is projected to range from $1.00 to $1.50 per gallon.

The effects of increased corn ethanol production on farm product prices, farm income, and Federal farm programs such as the Department of Agriculture price support program are relevant considerations in formulating national policy on fuel ethanol, but are not addressed in depth in this report. The effect of increased ethanol use on tax revenues is also an important consideration. When ethanol from renewable resources is used in ethanol/gasoline blends of at least 10% ethanol, the blend is exempt from $0.06 per gallon of the $0.09 per gallon gasoline excise tax, which in effect provides a subsidy of $0.60 per gallon of ethanol. At 85% ethanol blend levels this would not provide the depth of subsidy needed for ethanol production to be profitable. There is a blenders income tax credit that provides a subsidy of $0.60 per gallon of ethanol regardless of the ethanol content of the fuel. Without subsidies such as these, ethanol could not compete with gasoline at current or most projected prices.

Ethanol can also be made chemically from either ethylene or with more processing, ethane. Furthermore, ethanol can be made from non-food biomass such as lignocellulosic material from trees, grass, waste paper, and cardboard. Ethanol made from these sources is presently much more expensive than that made from corn; estimates range from $1.35-$2.40 per gallon according to information reported by the Department of Energy (DOE). DOE has ongoing research that may eventually provide improved technology for the conversion of biomass to ethanol. This research is working toward a long-term future goal of producing ethanol for $0.60 per gallon (plant gate cost, including capital recovery) without government subsidies. This goal is based on reducing feedstock costs from $3.00-3.25 per dry ton to $2.00 per ton. This depends on research success to improve average wood yields on selected test sites to 9-12 dry tons per acre per year from the approximate 7 tons per acre currently achievable. In addition, it depends on research to improve crop genetics and large-scale cultivation. While the long-term future cost of ethanol using these new technologies is highly uncertain, DOE is confident that research will result in significant cost reductions compared to the current cost of using cellulosic resources to produce ethnol, which is about $1.35 per gallon. DOE is continuing to work on future technologies that will improve the yield rate, the rate and concentration of the ethanol process, and lower the enzyme cost through biotechnology, as well as on system optimization and scale-up testing.[3-19,20] EPA has not independently considered whether the $0.60 cost is a realistic estimate, and EPA is aware that a number of organizations and experienced observers are unconvinced that it is realistic.

The only other country with a significant ethanol fuel industry is Brazil which makes ethanol from sugar cane at an annual production rate about six times that in the U.S. Brazil is currently experiencing a substantial shortage of ethanol because sugar cane production from which ethanol is produced has not matched the market demand for the fuel. Government planners have not been able to match ethanol supply with demand resulting in shortages of ethanol at the pump and irate consumers. Brazil is now attempting to import ethanol to meet demand. In addition, the high subsidy cost of the program to Brazil has contributed to budget problems.

Ethanol is presently shipped by tanker truck, rail, or barge and not by pipeline. In the long term, ethanol could be shipped by pipeline, but some initial added costs would be incurred to clean out and modify certain pipeline hardware for compatibility with ethanol. Ethanol shipping costs are estimated to be about $0.06 per gallon for a neat ethanol supplied to major ozone non-attainment areas, which compares to about $0.03 per gallon for gasoline supplied to these areas. However, ethanol has an energy content of 67% that of gasoline. Counting both transportation and service station mark-up, the actual pump price of ethanol not including a $0.60 per gallon Federal tax subsidy is projected to be about $1.28-1.30 per gallon when ethanol has a plant-gate price of $1.00 per gallon. This price would be $1.78-1.80 per gallon with an ethanol plant-gate price of $1.50 per gallon. These values do not include the 30% efficiency improvement for vehicles optimally designed for 100% ethanol. Incorporating a factor for this improvement and for the lower energy content of ethanol compared to gasoline (67%), the "gasoline-equivalent" ethanol price becomes $1.47-2.07 per gallon for the $1.00-1.50 per gallon ethanol plant-gate price without subsidy.

Due to the 30% increased efficiency possible with neat ethanol compared to gasoline, use of optimized vehicles fueled with neat (or less so with near neat) ethanol should allow use of smaller, lighter engines, and lighter suspension/body components all of which will tend to decrease vehicle costs. However, fuel system modifications for neat or near-neat ethanol might would tend to increase costs. Cold starting with neat ethanol at low temperatures would require solutions similar to those needed for neat methanol (e.g., separate fuel tank using gasoline or propane just for cold start or a direct fuel injection system). EPA assumes the savings and increases will balance out to zero with no overall cost difference between future optimized neat ethanol vehicles and gasoline vehicles. Flexible-fueled vehicles though require a fuel-sensor and do not have all the cost savings possible with a neat ethanol vehicle. EPA assumes an extra cost of $150-300 for a flexible-fueled vehicle.

Ethanol-fueled vehicles are expected to emit more ethanol and acetaldehyde than a gasoline-fueled vehicle with some smaller increases also possible for formaldehyde. The increased acetaldehyde emissions should lead to higher PAN (peroxyacetyl nitrate), but possible counterbalancing effects have not been explored. The limited non-methane hydrocarbon speciation data for ethanol-fueled vehicles suggest that the mix of non-methane hydrocarbons are not dramatically different for ethanol, methanol, and gasoline-fueled vehicles.

The impact of the use of ethanol-fueled vehicles on urban ozone has not yet been adequately studied. No quantitative modeling studies of any U.S. city exist involving 85-100% ethanol in vehicles. However, it is possible to calculate the relative reactivity of the projected composition of ethanol-fueled vehicle emissions versus that with gasoline. Some preliminary calculations have been done by Ford Motor Company and suggest about equivalent ozone benefits from vehicles fueled with ethanol and methanol.

Use of neat ethanol-fueled vehicles is expected to result in substantial air toxics benefits. For example, benzene is projected to account for about 20% of the carcinogenic emissions from gasoline vehicles in 2005 assuming that gasoline is not reformulated to reduce toxic benzene emissions, while combustion of ethanol fuel is expected to produce insignificant (if any) benzene. Similarly, ethanol is not expected to produce any significant 1,3-butadiene, polycyclic organic matter (POM), or gasoline refueling vapors, all of which have a substantial carcinogenic impact. However, as mentioned previously, ethanol fueled vehicles are expected to emit formaldehyde at a rate perhaps slightly greater than a gasoline vehicle, although less than that of a similarly engineered methanol vehicle.

Carbon dioxide is a major "greenhouse gas" which results from gasoline combustion. With ethanol, to the degree that it is derived from vegetation (i.e., trees or agricultural products) the reabsorption of the carbon can be as fast as it is emitted, resulting in no net increase in CO_2 in the atmosphere. However, about 7.4 million BTU of fossil fuels are currently used to grow one acre of corn, including fertilizer, pesticides, and grain drying. Fossil fuel is also used in the production of ethanol from that corn. There is some controversy on the quantities of these fossil fuel requirements and thus the resulting CO_2 impacts. Newer ethanol plants are significantly more efficient than older plants. Considering the amount of energy used for a newer plant (40,000 BTU per gallon of ethanol), it would be quite feasible to achieve a net CO_2 benefit of about 21-22% with incremental use of ethanol compared to gasoline. If cellulosic biomass is used as a feedstock instead of corn, even lower energy input per gallon is possible, and the energy could be derived from portions of the biomass rather than from a fossil fuel.

Substantially increased corn production for additional ethanol will have agricultural side effects (e.g., effects on surface and ground water from changes in water run-off patterns, soil erosion, wild life effects, and effects on forests if more land is cleared for crop production). A comprehensive treatment of issues such as these is beyond the scope of this report.

In the event of a major ethanol spill, ethanol's inherent properties of water solubility, biodegradability, and relative ease of complete evaporation, should allow it to quickly dilute to non-toxic concentrations, disperse downstream, and decompose if spilled into large bodies of water, or evaporate and decompose if spilled on land areas. Thus, in many scenarios, an ethanol spill should not be as hazardous as a petroleum spill. A tanker spill of ethanol into the ocean should pose less risk to aquatic life than a petroleum spill. Most scenarios where drinking water is at risk would be less severe with ethanol than with petroleum. In some situations, however, such as a river spill located very near a drinking water supply intake, ethanol may indeed contaminate a water supply that would have escaped contamination by a petroleum fuel.

Leaks into underground water are a potentially greater concern with all fuels because of the more restricted dilution conditions that can exist. Also, while bacteria are present in soil and underground water supplies, they are sparser than in the ocean and surface waters. Ethanol and petroleum fuels have different hydrological effects in soils and may migrate downward at different rates, providing more or less time for evaporation instead. Once in contact with the water table, ethanol will tend to mix and dilute more quickly than a petroleum fuel and to biodegrade more quickly, although there may be a zone in which the ethanol concentration is too high for biodegradation to occur. If ethanol reaches a drinking water well, there is little health risk since consumption of drinking water with low levels of ethanol should not be acutely toxic, with the possible exception of fetuses and pregnant women.

Ethanol, like all combustible fuels such as gasoline, poses a potential human safety risk from vehicle fires. Ethanol's low volatility, relatively high lower flammability limit, and low vapor density relative to gasoline cause it to be much less likely to ignite in an open area following a spill of fuel or release of vapor. In addition, once it does ignite, ethanol's low heat of combustion and high heat of vaporization cause it to burn much more slowly, releasing heat at roughly one-fifth the rate of gasoline. However, these same combustion properties cause ethanol to be in the flammable range inside fuel storage tanks under normal ambient temperatures, while gasoline is virtually always too rich to ignite. Fortunately, precautions can be taken to prevent either flammable vapor/air mixtures from forming in storage tanks (e.g., nitrogen blanketing, bladder tanks, floating roof tanks) or to prevent ignition sources from entering the tanks (e.g., flame arresters, removing or modifying in-tank electrical devices) thereby mitigating any additional risk. These actions will increase costs. Also, ethanol tends to burn with a visible flame (much more visible than methanol but not quite as visible as gasoline).

Most gasoline ingestions episodes are due to adults attempting to siphon gasoline from a vehicle, or children drinking from small containers of gasoline intended for use in small household engines or for degreasing. Ethanol-fueled vehicles can be equipped with devices to prevent siphoning (and the same device could serve as a flame arrester). Ethanol fuel storage in homes should be rare, since household engines will not run on ethanol and ethanol would not be a good degreaser. Also, ingestions of several ounces of pure ethanol would not be harmful to most adults although it would be of concern for a child. However, the denaturant may be toxic, and it is important for the denaturant to have an unpleasant taste and smell to discourage ingestion.

Despite the presence of the denaturant, fuel ethanol may be deliberately or mistakenly added to beverages. Incidences with methanol were common in the past in the U.S., and bootlegbeverages made with ethanol fuel could be of health concern due to the denaturants. Unsophisticated users may not understand the risk posed by the denaturant or may mistakenly believe they have removed or neutralized it. Consumer education is needed, and as stated above, it is important for the denaturant to have an unpleasant taste and smell to discourage ingestion.

1.0 INTRODUCTION AND GENERAL CONCEPTS

In 1988, U.S. production of ethanol for use as a motor fuel blend was about 840 million gallons. As such, ethanol is the highest-volume alternative, i.e., non-petroleum motor fuel. It is also the only non-fossil, and therefore at least in part renewable, liquid fuel in commercial use. If this volume of ethanol had been used only in its pure form rather than as a blending agent, it would have been enough to fuel almost a million vehicles, which is far more than the number of vehicles operating on other alternative fuels such as electricity, methanol, CNG, LNG, propane, or LPG.

Currently, however, there are no U.S. vehicles regularly operating on neat or near-neat ethanol.* Rather, the ethanol produced domestically, and a small quantity of imported ethanol, is splash blended into gasoline at 10 percent concentration. This allows the ethanol to be used by vehicles originally designed to operate on gasoline. Sales of ethanol-gasoline blends, or gasohol, are geographically non-uniform due largely to availability of state specific tax subsidies. Gasohol's market share is low in the large urban areas of the East and West Coasts. In many Midwest markets, gasohol comprises about 30 to 40 percent of sales where states provide significant subsidies in addition to the Federal subsidy. Overall, the U.S. market share is about 7.5 percent. Ten years ago it was essentially zero. The market share has been relatively stable over the past two or three years. This level of use is a result of the $0.60 per gallon Federal subsidy costing about $500 million per year plus state subsidies ranging up to $0.40 per gallon and totalling roughly $160 million per year. These subsidies are needed because the current cost of ethanol is over two times that of gasoline on an energy equivalent basis, and thus it is not economically competitive with gasoline.

Ethanol production and its use in motor vehicles in the form of gasohol have been the subject of numerous studies, political debates, and legal proceedings over the last ten years, because of the many areas of public policy that are involved: agricultural, energy security, highway funding, environment, tax, budget and economic costs, foreign trade, and interstate commerce. The more important Federal studies are listed later in this report. Due to all this existing documentation on gasohol, this report will not address the use of these blends.

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* Pure ethanol will be referred to as "neat" ethanol or "E100", and if blended with small quantities of gasoline will be referred to as "near-neat" or for example "E85".

It should be noted, however, that a potential expanded use of ethanol is in reformulated gasoline, where ethanol could be used at low concentrations directly or as ETBE (e.g., 10% by volume for ethanol or possibly up to 22% for ETBE). A Federal subsidy of $0.60 per gallon of ethanol would be needed since ETBE is not economically competitive with MTBE, which is the other oxygenated high octane component most likely to be used in reformulated gasoline. Ethanol would provide needed octane and oxygenation, and in the case of ETBE it would also provide pipeline fungibility and aid in RVP reduction. This application of ethanol is more appropriately addressed in a study of reformulated gasoline, which is planned to be done after specific reformulation(s) have been determined.

This report focuses not on gasohol, but rather on the potential use of neat (i.e., 100%) ethanol (referred to as E100) or near-neat ethanol (e.g., E85) in vehicles specifically designed for operation on ethanol or alcohols in general. Such potential use is briefly mentioned in some of the past studies that emphasized gasohol, but no comprehensive analysis relevant to the 1990's and later timeframe has been published. This report is reasonably comprehensive in that all considerations currently known to be important are addressed to some degree or at least mentioned. However, it is not meant to be a thorough review of all the relevant literature, nor is it a complete de novo analysis of issues on which the literature is inconclusive or out of date.

The following paragraphs provide a conceptual context for the remaining sections of this report.

It is necessary to recognize that there are several possible scenarios as to how ethanol could be used as a motor vehicle fuel. The cost and other impacts of these scenarios may differ from one another. On the fuel side, fuel-grade ethanol can take several forms. The most "natural" form would be hydrous ethanol, the mixture of 95 percent ethanol and 5 percent water that results from distillation of a fermented liquid. This, usually with 3% gasoline as a denaturant, has been the form of ethanol most widely used in Brazil, at least up until a recent ethanol supply vs. demand shortfall, to which the Brazilian government has responded by adding 5% gasoline to the ethanol/water mixture as well as importing ethanol. In the U.S., hydrous ethanol would always have to be denatured by adding poisonous or unpalatable ingredients to distinguish it for tax purposes from beverage ethanol.

A vehicle designed to operate on hydrous ethanol could differ from a gasoline vehicle in several respects (in some respects it would have to differ). Because of the lower energy content of ethanol, the fuel delivery system would have to deliver more fuel per engine cycle. Attention would also have to be paid to material compatibility, although ethanol does not pose any particular difficulties in this regard, since materials changes would be no greater than (and in some cases would be less than) those needed for methanol vehicles. Because of ethanol's higher octane, the compression ratio would be higher than with gasoline, resulting in greater fuel efficiency and power density. Ethanol's combustion properties (e.g., flame speed) would also increase efficiency and power. Combustion temperature and therefore oxides of nitrogen (NOx) formation are expected to be lower with ethanol than with gasoline. The water content of hydrous ethanol also works to control NOx formation. This creates the possibility that a fuel efficient lean-burn ethanol engine could meet the current 1.0 gram per mile NOx emission standard, and perhaps even a more stringent standard, without catalytic aftertreatment for NOx. (For NOx limits of 1.0 gram per mile or lower, gasoline engines require catalytic aftertreatment for NOx, which in turn dictates less fuel efficient operation at stoichiometry.) There could or would also have to be other less significant differences in emission control system design, for example the distance between engine and catalytic converter.

As will be discussed in the next section, pure hydrous ethanol has a very low volatility, too low to allow a vehicle to be reliably started if the starting system on the vehicle is of the sort now used on gasoline vehicles. In Brazil, ethanol vehicles have a separate smaller gasoline tank for starting and operating until warm enough to tolerate the low volatility ethanol. Other approaches for cold starting hydrous ethanol-fueled vehicles are also possible. One would be to use a gaseous fuel such as propane, LPG, or CNG instead of gasoline as the starting fuel. With sufficient development, it would also be possible to rely on engine hardware entirely, such as direct injection with glow plugs rather than a second starting fuel.[1,2]

Another approach to cold starting would be to blend the ethanol with a second, more volatile fuel such as gasoline or a low molecular weight hydrocarbon. If enough volatility is added, a vehicle with a conventional starting system can be reliably started on the ethanol mixture. This would be the ethanol equivalent of "M85," a mixture of 85 percent methanol and 15 percent gasoline. It would also make it simpler to design a flexible fuel vehicle (FFV) that can operate on gasoline or ethanol. In fact, the many FFV prototypes already produced with M85 as the intended alternative fuel could operate on a mixture of gasoline and ethanol if the mixture were volatile enough. The next section examines what mixture would have enough volatility.

One complication of a gasoline/ethanol mixture is that under certain conditions of temperature and gasoline content the ethanol portion must be water-free, or anhydrous. Otherwise the ethanol and gasoline will not stay mixed. This requires an additional dehydration process after distillation, which necessarily adds to plant investment and operating cost. (Ethanol used now in gasohol blending is anhydrous.) There is no reason vehicles could not be specially designed for anhydrous rather than hydrous ethanol, but there is no strong reason to incur the additional cost of dehydration unless the ethanol will be blended with a substantial percentage of gasoline (e.g., over 30% gasoline) or another non-polar liquid.

Transition and application issues are important in any consideration of an alternative fuel such as neat or near-neat ethanol. There are some applications in which ethanol fuel and dedicated vehicles designed to operate only on ethanol can be introduced together, such as in dedicated delivery fleets. Such fleets are or could reasonably be refueled at a small number of new ethanol refueling facilities. For the general vehicle population, operators are accustomed to being able to refuel virtually anywhere. This requires the availability of ethanol at a significant fraction of retail gasoline stations and/or the ability of ethanol vehicles to operate on gasoline (or another widely available fuel) when ethanol is not available, i.e., a flexible fuel ethanol vehicle. Widespread availability of ethanol would pose an overhead cost per vehicle in the early years of a transition, when relatively few ethanol vehicles are on the road. This transition cost issue would also exist with any alternative fuel other than reformulated gasoline. It would be more of an issue with ethanol than, say, methanol, in that the supply of ethanol from corn will be more constrained and variable since it would be dependent on levels of agricultural production that can vary widely with the weather.

As stated earlier, an FFV designed for M85 can also operate on an ethanol-gasoline blend if the vapor pressure of the blend is within the seasonal range contemplated by the FFV designer. Other FFV concepts are also possible. A neat ethanol vehicle with special cold starting hardware (either a second fuel or a special cold start approach) could rather easily be produced in FFV form so that it could also operate on gasoline or mixtures of gasoline and ethanol. Because of the possibility of encountering in-tank mixing of fuels, any FFV must use anhydrous ethanol.

Any vehicle designed to be able to operate on any combination of gasoline, ethanol, or ethanol-gasoline mixtures would entail some performance or cost compromises. For example, unless some costly means of providing variable effective compression ratio is used (e.g., turbocharging with variable boost according to fuel), compression ratio must be set to accommodate the lowest octane fuel expected, or significant spark timing retard must be used on the lower octane fuel, hurting fuel economy and power. Fuel tank capacity will be either somewhat oversized on gasoline or somewhat undersized on ethanol. Various engine and emission control components may need to be duplicated or otherwise compromised in performance or increased in cost. For these reasons, in order to take full advantage of ethanol as a fuel it would be necessary to design vehicles to be dedicated to ethanol, or at least to alcohol fuel more generally. This is true for both neat alcohols, and alcohols blended with a higher volatility component.

The more important advantages of a dedicated ethanol vehicle over an FFV include lower first cost due to elimination of gasoline-capable components (e.g., fuel type sensor), fuel efficiency, generally less ozone potential from exhaust emissions, and less evaporative and refueling emissions. On the other hand, FFV's have the advantage of greater fuel availability. Also, if all the usable fuels are available in high RVP form such as E85, vehicles designed for such fuels would have the advantage of a less expensive means of low temperature starting than dedicated E100 vehicles or FFV's designed to be able to start on E100.

While alcohol-dedicated vehicles would be superior to flexible fuel vehicles for performance and emissions, they do not necessarily have to be dedicated to a particular alcohol. Because of the different stoichiometric ratios of different alcohols, some special features are needed for a multi-alcohol vehicle that would not be needed on a vehicle designed for a particular alcohol. For example, the same fuel type sensor used in M85 FFV's to distinguish gasoline from M85 (and mixtures between the two) could distinguish methanol, ethanol, and other alcohols well enough to allow for multi-alcohol capability. Other approaches might also be possible. The major cost difference from dedicated M100 vehicles would be the fuel sensor just mentioned plus possibly a more costly low temperature cold starting system for E100 capability.

The production of vehicles with multi-alcohol capability might make several scenarios theoretically possible that otherwise would be more difficult to achieve because of scale or transition problems. A detailed assessment of the costs is not available. Methanol might be more economic than ethanol on the east and west coasts, but ethanol with federal and state subsidies might be more competitive in Chicago. The Chicago vehicle market might be too small to support the production of special ethanol-dedicated vehicles. But if all or most methanol vehicles were ethanol compatible, Chicago may prefer ethanol instead of methanol. Also, multi-alcohol vehicles might be purchased by government fleets and fueled with neat ethanol in corn belt states, or such states might offer local subsidies large enough to make ethanol fuel attractive even to private users. Another scenario would be that some or all areas begin with only a methanol fuel supply system, but ethanol would face no "chicken-or-egg" market entry barrier if production economics shift in its favor or if public policy changes to more strenuously promote ethanol due to its renewability or other aspects not presently valued by the market. Pipelines, barges, tank cars, tank trucks, storage tanks, and vehicles could be switched from methanol to ethanol virtually overnight.

If multi-alcohol capability by vehicles were accompanied by a requirement for availability of both methanol and ethanol fuel in the same area, there would be costly duplication of supply infrastructure.

As a final note, there may be some engine types for which flexibility between ethanol and methanol would not be readily feasible. For example, the carbon-carbon bond in ethanol might present a smoke/soot problem in certain engine designs that would not have such a problem with methanol.

It must be noted that while a vehicle can be designed to operate on a range of alcohols with good driveability and fuel economy on all, its emission characteristics will tend to be dependent on the particular alcohol being used. Even more so, an FFV that can operate on gasoline or alcohol may have very different emission characteristics on the two fuels.

Although a good bit of ethanol vehicle development has been done in Brazil, those vehicles are not representative of what would exist in the U.S., since the emission control technology in use there is equivalent to early 1970's U.S. technology. In the United States much more vehicle development has been undertaken for methanol than for ethanol. Section 2 discusses the properties of ethanol and the degree to which the methanol development results are applicable to ethanol in light of the similarities in their engineering properties.

Sections 3 and 4 of this report then discuss the economic and environmental considerations raised by the various scenarios outlined above.

References Cited in Section 1

1. Statement of Work, EPA Contract 68-C9-0002, "Glow Plug Ignited Direct Injection M100 Vehicle," Project Officer Robert I. Bruetsch, start date January 1, 1989.

2. Statement of Work, EPA Contract 68-C0-0007, "Spark Ignited Direct Injection Methanol Vehicle," Project Officer Robert I. Bruetsch, start date March 1, 1990.

2.0 PROPERTIES OF ETHANOL

Table 2-1 lists the properties of ethanol relevant to its use as a fuel along with those of methanol and typical gasoline for comparison. Whereas gasoline is a mixture of hundreds of different hydrocarbon compounds with a wide range of individual properties, ethanol and methanol are single components with well-defined properties.

As shown in Figure 1, the vapor pressure of ethanol is much lower than gasoline, and about half that of methanol.[1,2] The low vapor pressure of ethanol, combined with the high heat of vaporization (about 2/3 that of methanol) relative to gasoline, means that low temperature startability and driveability would require vehicle and/or fuel modification to a similar or greater extent than a methanol vehicle.[2,3,4]* This could include approaches such as intake system heaters, auxiliary startup fuel systems with propane or gasoline, higher volatility fuel additives (e.g., gasoline) or use of a different engine concept such as direct injection.[3,5-8] It also raises the potential for even lower evaporative and running loss emissions than with methanol.

In the case of using only fuel modifications with no hardware changes to improve the cold startability of ethanol, some insight into possible solutions can be gained by comparing it to the methanol case. As one specific point of comparison, M85 made with 15% 9.0 psi RVP gasoline provides an RVP of roughly 8.0 psi. Using 9.0 psi gasoline would have the advantage that it could be the same gasoline in general use for gasoline fueled vehicles; however, to achieve an RVP of 8.0 psi in ethanol would require 40% of a 9.0 psi RVP gasoline, but this is not envisioned as a realistic solution since it would negate much of the potential benefits of ethanol. Another approach could be to use 15% of a higher RVP gasoline, although this would present greater distribution problems due to not being able to use the generally available lower RVP gasoline. In fact, due to the very low RVP of ethanol, a gasoline RVP greater than 15 psi may be needed for an E85 fuel. Another approach could be to use a high RVP blending component such as butane or isopentane, which might be more plentiful with the reduced gasoline RVP limits. In the case of isopentane, a final RVP of 8.0 psi could be achieved by adding roughly 7.5% isopentane to ethanol or 4.5% isopentane to methanol.[1]

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* Although vapor pressure is an important factor in cold startability, the higher stoichiometric air:fuel mass ratio of ethanol (E100) and its higher molecular weight should combine to make the startability of ethanol closer to methanol (M100) than would be expected based only on their vapor pressures. The ratio of MeOH to EtOH stoichiometric A:F ratios (6.5/9.0), times the ratio of MeOH to EtOH molecular weights (32/46) gives about 0.5, indicating that the vapor pressure of the EtOH only needs to be half that of methanol to yield an equivalently combustible mixture. This does not take into account other dynamic factors such as the effects of heat of vaporization or lean combustion limits.

It has been technically demonstrated by the Nebraska Ethanol Board that under summer conditions a lower RVP E85 fuel made from commercial gasoline of roughly 9.0-9.5 psi can provide adequate startability in at least certain vehicle designs. The final RVP of this fuel was not measured but should have been below 8.0 psi. The vehicle used had been retrofitted from gasoline rather than being a vehicle designed and optimized for ethanol operation. This, of course, is not a complete market based test over a range of consumers, driving conditions and vehicles.

The heating value (energy content) of ethanol is about 2/3 that of gasoline and 1/3 greater than methanol. Since other combustion related properties (e.g., high octane, high heat of vaporization, and lean combustion capability) would allow efficiency improvements similar to those of methanol, a given vehicle operating range (miles per tankful) could be obtained with a smaller fuel tank than with methanol. Alternatively, in the case of an FFV, a given fuel tank size would allow a greater operating range on ethanol than methanol.

The flammability limits and vapor pressures of ethanol indicate that a combustible mixture of ethanol in air would exist over the same temperature range as methanol. Therefore, it is expected that a flame arrester would be called for on the fuel tank fill neck of a neat ethanol vehicle as with methanol vehicles to prevent ignition from a spark or flame entering the fill neck. However, in Brazil flame arresters have not been used, and no problems have been reported. (It is not known how systematically reports of any problems would have been collected and reported.) Another aspect of the flammability issue is the possibility of ignition from a source inside the tank such as a spark from an in-tank electric fuel pump and built-up static electrical charge. Again, Brazil has not reported any problems of this type, but in general Brazilian vehicles are carbureted rather than fuel injected, and in-tank fuel pumps are only used with fuel injected vehicles. Another possible factor in this flammability question is that alcohol fuels have a much higher electrical conductivity than gasoline and are thus less prone to build up static charge. This could result in a lower tendency to ignite than is suggested by their flammability limits. In the case of E85, the volatility would be high enough to avoid a combustible mixture over a wide temperature range.

Methanol (M100) and ethanol (E100) should have nearly the same low tendency to ignite if spilled. If ignition were to occur, it is uncertain which type of fire would produce more damage. The higher energy density, higher luminosity, and lower heat of vaporization would tend to make ethanol burn hotter, brighter, and faster than methanol, but the lower vapor pressure would have the opposite effect. The net effect of these factors is not known, but as with methanol the rate of heat release should be much less than with gasoline.

Based on references and a small EPA in-house experiment burning small amounts of different fuels, the luminosity of neat ethanol is much better than methanol.[3] Although it is not as visible as gasoline, it does burn with a bright orange flame rather than the blue flame of methanol, and it is visible enough that no luminosity additives may be required. Additional luminosity might come from the additives that would be called for even if the low temperature driveability problems are handled without fuel modification. For instance, since ethanol in its drinkable form is subject to beverage taxes, a denaturant would be needed to make it undrinkable. Then, if the denaturant itself did not modify the smell and taste of the fuel, some additive would be needed to make the fuel smell/taste bad enough to deter attempts at consumption.

Water tolerance is an issue that must be considered when mixing ethanol or methanol with gasoline. Depending on the temperature, alcohol content, water content, and gasoline formulation, a mixture of alcohol and gasoline can phase separate, which results essentially in one phase containing the ethanol and water with the second phase consisting of gasoline. The water tolerance of a given ethanol gasoline blend can be considered as the temperature below which, or the water content above which, phase separation begins. This is mainly a concern when considering FFV's, where a variety of fuels could be used. This is discussed more fully in section 3.1.1.3 in connection with the use of hydrous versus anhydrous ethanol.

Regarding emissions, the high heat of vaporization, low flame temperature, and lean combustion capability of ethanol, as with methanol, result in a potential for lower NOx emissions than with gasoline. A NOx standard of 1.0 g/mile may be able to be met using a lean air:fuel calibration without a 3-way catalyst, but lower standards such as 0.4 or 0.2 g/mile would be more difficult to meet and could require a more costly solution similar to gasoline vehicles. The quantity of volatile organic exhaust emissions and ozone forming potential of ethanol fueled vehicles are expected to be similar to those from similarly engineered methanol vehicles. Section 4.0 provides the details of this.

The lower volatility of neat ethanol relative to neat methanol would tend to produce even lower evaporative emissions. M85 and E85 of similar volatility would not necessarily produce similar evaporative emissions. Since the E85 would require a higher vapor pressure gasoline to operate in the same type of vehicle, the evaporative emissions would have a higher proportion of gasoline vapor than with M85. Furthermore, if a cold-start system is used that uses a second fuel such as gasoline, there would be added potential for evaporative emissions from it. The expected effects of these factors on ozone formation are discussed in section 4.1.

Table 2-1

Fuel Properties

	Ethanol	Methanol	Gasoline
Vapor Pressure, psi @100°F	2.5	4.6	8-15 (RVP)
Vapor Pressure, psi @115F	3.2	6.4	12.5*
Vapor Pressure, psi @40F	0.4	0.8	3.1*
Lower Heating Value, BTU/gal	76,000	57,000	114,000
Research Octane	111	112	91-98
Motor Octane	92	91	83-90
Heat of Vaporization, BTU/gal	2380	3390	930
Specific Gravity	0.789	0.796	0.70-0.76
Boiling Point (°F)	173	148	80-400
Molecular Weight	46.07	32.04	100-105
Grams Carbon/gal	1558	1124	2421
Stoichiometric A/F Ratio	9.0	6.5	14.5
Flammability Limits (vol%)	3.3-19	6.7-36	1.4-7.6
Flash Point (°F)	55	52	-45
Auto Ignition Temp (°F)	423	464	257

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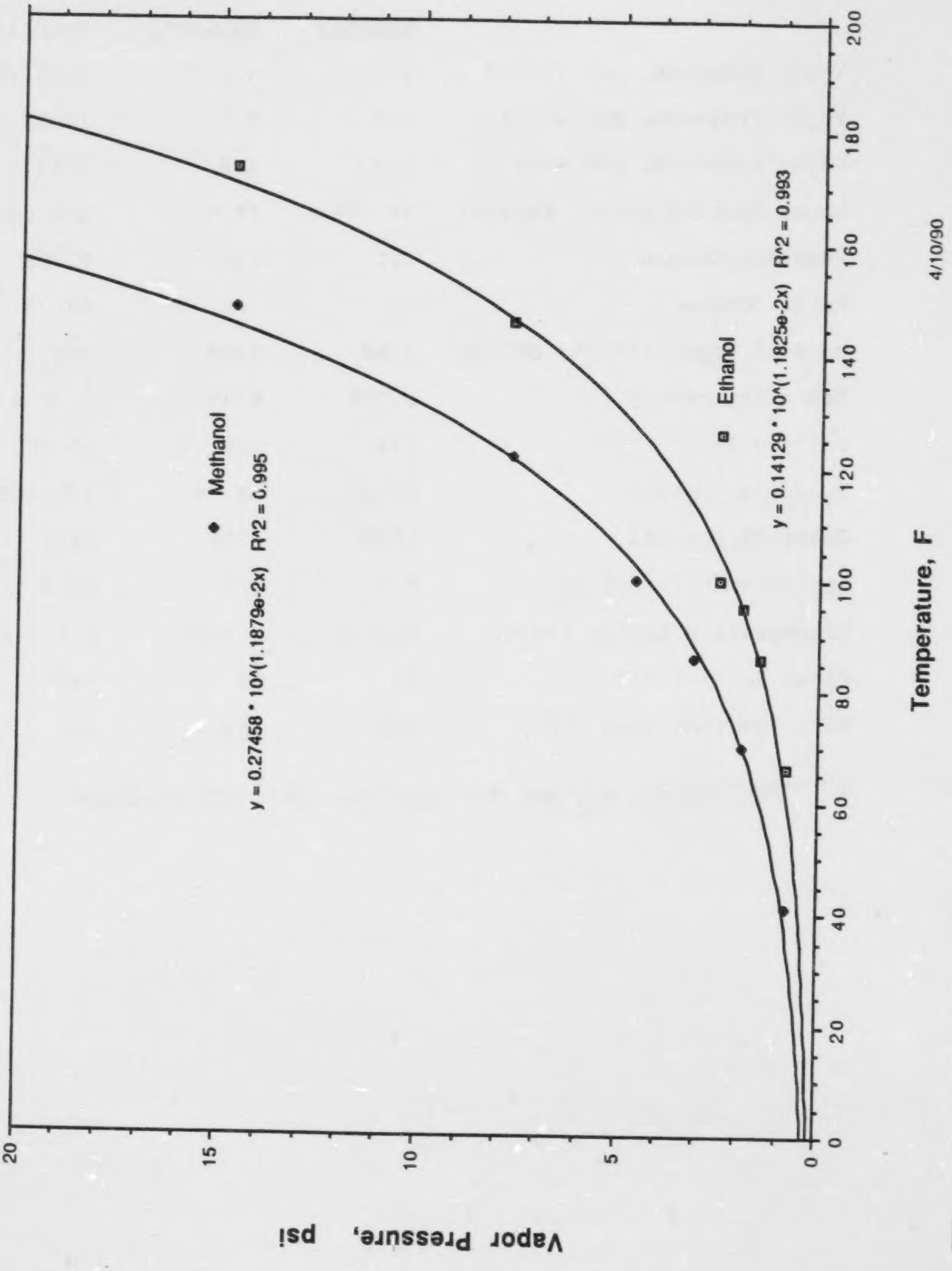
* For typical 9.0 psi RVP gasoline, per ASTM Handbook.

Figure 2-1

VAPOR PRESSURE vs TEMPERATURE
Methanol and Ethanol



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2. "Volatility Characteristics of Gasoline-Alcohol and Gasoline-Ether Fuel Blends," Robert L. Furey, GM, SAE Paper 852116, October 1985.

3. "Ethanol Fuel Modification for Highway Vehicle Use - Final Report," U.S. Department of Energy, Report ALO-3638-T1, July, 1979.

4. "Vapor Pressure and Weatherability of Blends of Methanol and Ethanol with Gasoline," A. L. Titchener, D. Hyde, and A. Hoskin, VII International Symposium on Alcohol Fuels, October 20-23, 1986.

5. Statement of Work, EPA Contract 68-C9-0002, "Glow Plug Ignited Direct Injection M100 Vehicle," Project Officer Robert I. Bruetsch, start date January 1, 1989.

6. Statement of Work, EPA Contract 68-C0-0007, "Spark Ignited Direct Injection Methanol Vehicle," Project Officer Robert I. Bruetsch, start date March 1, 1990.

7. "The Use of Ethanol from Biomass as an Alternative Fuel in Brazil," H. Hertland, H. W. Czaschke, and N. Pinto, II International Symposium on Alcohol Fuels, 1977.

8. "Aspects of the Design, Development and Production of Ethanol Powered Passenger Car Engines," F. B. P. Pinto, VI International Symposium on Alcohol Fuels, May 21-25, 1984.

3.0 ECONOMIC ANALYSIS OF ETHANOL

3.1 Domestic Production

3.1.1 Fermentation From Grain

3.1.1.1 Previous Federal Studies

There are three major comprehensive studies that have been done by the Federal government on use of ethanol as a motor fuel examining its economic and environmental aspects. These studies were used to provide input for this report as appropriate.

1. "Fuel Ethanol and Agriculture: An Economic Assessment," U.S. Department of Agriculture, August 1986.[1]
2. "Fuel Ethanol Cost-Effectiveness Study," Final Report of the National Advisory Panel on Cost-Effectiveness of Fuel Ethanol Production, November 1987.[2]
3. "Ethanol - Economic and Policy Tradeoffs," U.S. Department of Agriculture, January 1988.[3]

Copies of the executive summaries of the latter two more recent reports are included in Appendix A.

A fourth reference is the August 23, 1989 Department of Agriculture press release titled "Ethanol's Role in Clean Air."[4]

3.1.1.2 Current U.S. Ethanol Production

Table 3-1 shows the amount of domestic ethanol produced and used as a fuel blending agent from 1980 through 1988.

Table 3-1

Domestic Ethanol Used as Fuel

Calendar Year	Fuel Ethanol (million gallons per year)
1979	20
1980	40
1981	75
1982	210
1983	375
1984	430
1985	625
1986	750
1987	825
1988	about 840

Introduction of neat or near-neat ethanol for new vehicles in certain areas of the country would require an expansion of this production by roughly a factor of two for approximately a million vehicles unless some of the current production were diverted. Expansion beyond this number of vehicles would require correspondingly larger expansion in the amount of ethanol produced. While there is already a significant amount of ethanol being produced for blending with gasoline in 10% ethanol mixtures, ethanol usage as a primary fuel in a large portion of in-use vehicles would require a sizable expansion of supply. Production of ethanol at 5 times the current level would support a fleet of about 5,000,000 vehicles; at steady-state, this would correspond to annual sales of about 500,000 vehicles. At this level about 20% of the total current U.S. corn production would be used. The Department of Agriculture has stated in its August 1989 press release mentioned above that increases in ethanol production exceeding 4 to 5 times current levels would begin to tax agricultural resources and place upward pressure on grain prices, thereby increasing the cost of ethanol (and food).

While it would be fair to say that the limit of production from grains is not well defined, as ethanol demand increases relative to corn supply, ethanol supply and/or food prices would become more vulnerable to temporary shortages in corn supply, such as due to weather. For example, in 1988, U.S. corn production declined by over 30 percent because of the drought, while ethanol production increased about 2 percent from the previous year in part due to stockpiled corn. In 1983, corn production dropped by about 50% from 1982 levels due partially to greater government land diversion incentives that year and partially to drought. Sharp declines in production of corn could result in major ethanol shortages for fuel purposes which must be carefully considered in evaluating ethanol as a fuel. However, the use of stockpiles of either corn or ethanol would mitigate such effects by in effect averaging production fluctuations over several years, although there may be a large cost associated with operating a truly adequate stockpile. The cost of an ethanol stockpile is estimated at $0.02-.06 per gallon per year based on data gathered by USDA assuming at least a five year residence time in storage.[5] Stockpiling corn would be more expensive at about $0.26-.31 per bushel per year ($0.10-.12 per gallon of ethanol)[6], but would maintain flexibility for alternative uses of the corn.

3.1.1.3 Hydrous Versus Anhydrous Ethanol

The ethanol used in making current low level ethanol-gasoline blends (e.g., 10% ethanol or gasohol) is virtually water-free (i.e., anhydrous, 199 proof, before addition of any denaturant). However, this may not be necessary for neat ethanol vehicles, and there is a potential for economic and energy benefits if ethanol production could end with hydrous ethanol (5% water) rather than continue through the final dehydration step to yield anhydrous ethanol.

The reason anhydrous ethanol is necessary in low level blends is the poor water tolerance of gasoline-ethanol blends at low ethanol concentrations. A very small amount of water in such blends can cause phase separation, in which the water pulls most of the ethanol out of solution from the gasoline resulting in two layers or phases of liquid in the fuel tank. One of the phases is almost pure gasoline, but the other phase is basically a mixture of water and ethanol, which a vehicle cannot operate on and which can accelerate rust formation.

In the case of neat or near neat ethanol there would be either no gasoline or only enough gasoline to provide volatility for cold startability. Water tolerance data have been collected by the Department of Energy ("Ethanol Fuel Modification for Highway Vehicle Use") at 68°F for the full range of ethanol/gasoline/water blends.[7] At this temperature, hydrous ethanol (190 proof, 5% water) could be mixed with up to about 80% gasoline before phase separation would begin. However, lower temperatures are known to decrease water tolerance.

Some limited water tolerance test data for mixtures of up to 79% hydrous ethanol with gasoline at temperatures down to 0°F have been supplied to EPA by the Renewable Fuels Association.[8] According to these data, 79% hydrous ethanol (E79) would have no phase separation down to 0°F, and by extrapolation greater ethanol concentrations would provide tolerance at even lower temperatures. Another reference that tends to support this conclusion was provided by GM, but covers ethanol concentrations only up to 40%.[9] In this study at 0°F (-18°C) a mixture of 40% ethanol and 60% gasoline could tolerate 0.95% water, and the tolerance was increasing greatly with increasing ethanol concentration. Therefore, E95 and even E85 probably have sufficient water tolerance to allow use of hydrous (5.0% water) ethanol even at temperatures below 0°F.

In Brazil, neat hydrous ethanol is used in the majority of light-duty vehicles. Currently, this ethanol includes 5% gasoline, and no phase separation problems are expected due to the small concentration of gasoline and the temperature range of Brazil.[10] Before hydrous ethanol could be used in the U.S. in the winter with any added gasoline, research would be needed to confirm the exact gasoline content versus temperature limits for acceptable water tolerance.

In the case of FFV's, which could be fueled with gasoline or E85, anhydrous ethanol would need to be used. The reason for this is as follows. If hydrous ethanol (5.0% water) were used to create an E85 fuel, the resulting water content would be 4.25%. If straight gasoline were then added to this in the fuel tank of an FFV to dilute the ethanol to a concentration of 40%, the water content would be 2.0%, which is above the 0.95% limit at 0°F. Therefore, in mild parts of the country or during summer months there would probably not be any problem, but in colder weather there could be a problem with phase separation of hydrous ethanol when used in FFV's.

Another issue to be considered regarding the use of hydrous ethanol would be maintaining separation of hydrous and anhydrous ethanol in the distribution system, since only anhydrous would be acceptable for use in low level ethanol blends. This is presumed to be feasible in the U.S. since Brazil now does it. Also, in the near term, any use of hydrous or anhydrous ethanol will involve special handling since pipeline companies will not currently ship it. Since this is already the case with the anhydrous ethanol used in 10% ethanol blends, the only additional precaution needed for handling of hydrous ethanol would be clear labeling to keep it from being mixed with anhydrous ethanol or with gasoline. In the long term, if pipelines carry ethanol, they will need to be cleaned and made water-free regardless of which type of ethanol is carried. In fact, once this was done, an occasional shipment of hydrous ethanol could be used to help keep the system free of water. In Brazil it has been found that when shipping hydrous ethanol in a gasoline pipeline, a shipment of anhydrous ethanol should be scheduled at both ends of the hydrous shipment to avoid phase separation at the interface of the hydrous ethanol and gasoline.[9]

Some very preliminary analyses have been done concerning the potential cost and energy savings associated with production of hydrous versus anhydrous ethanol. Traditionally, the dehydration of hydrous to anhydrous ethanol is done with a process called azeotropic distillation, which involves the addition of a hydrocarbon such as benzene or cyclohexane to the ethanol/water mixture followed by a final distillation. Leaving out this step could save roughly 3-6 cents per gallon of ethanol, including savings in both operating costs and capital costs.[10,11] There are many factors influencing this value, such as plant size and configuration, corn price, labor rates, interest rates, etc. An added benefit of being able to neglect this final distillation step would be to decrease the fossil fuel use and thus improve the net global warming effect of ethanol fuel use.

A more recent dehydration technology used by Archer Daniels Midland (ADM) in all its ethanol plants makes use of corn grits to adsorb the water out of the hydrous ethanol.[12, 13] The grits are then recycled by driving off the water with a hot inert gas. ADM estimates this process to yield a total cost savings of 2-3 cents per gallon over the traditional azeotropic distillation.[14] Another dehydration technology that is just starting to be implemented involves the use of molecular sieves.[15] This is considered most cost effective for ethanol plants smaller than those operated by ADM. Therefore, when comparing the costs of hydrous versus anhydrous ethanol for plants already utilizing either of these new technologies, the savings will be less than if the traditional dehydration azeotropic technology is assumed.

3.1.1.4 Corn and Ethanol Production Economics

Each bushel of corn yields about 2.5-2.6 gallons of ethanol. Either of two processes is used to convert corn to ethanol.

The first is the dry milling process which involves milling the grain but not separating its components before the "mashing" process. Starch in the mash is converted to sugar and then to ethanol by the action of yeast. The dry milling process also yields distillers dried grains with solubles (DDGS), a common protein animal feed. Current technology yields 16.5-17.5 pounds of DDGS from a bushel of corn. In some plants the carbon dioxide from fermentation is also trapped and sold for industrial or beverage uses, but this is not a universal practice.[12]

The second process is the wet milling process which accounts for about two thirds of the ethanol produced. In wet milling, corn is first separated into its major components (germ which can be dried separating out the oil, fiber, gluten, and starch). The starch is then converted into either ethanol or high-fructose corn syrup (HFCS) depending on the relative market demand and price of each. The former is usually produced more in the winter and the latter in the summer when demand is high for HFCS. Also, as with dry milling plants, the carbon dioxide produced from fermentation is sometimes captured for sale.[12] Wet milling plants also produce higher value byproducts such as corn gluten feed and meal. As a result of their broader product mix these plants have more marketing flexibility than dry milling plants. Wet milling is generally more complex and capital intensive than dry milling.

Corn and byproduct prices are important factors in determining ethanol costs; about 95% of the fuel ethanol produced in the U.S. comes from corn, with most of the rest coming from other agricultural products such as milo (grain sorghum), wheat, barley as well as food and industrial wastes. It is expected that at either current or expanded production volumes, most fuel ethanol will continue to come from corn for at least the next 8-10 years due to cost factors. The corn crop has been about 7-8 billion bushels a year for the past few years except in 1988 when production dropped to less than 5 billion bushels due to a severe drought. About 325 million bushels of this has gone to fuel ethanol each year. According to the 1988 Department of Agriculture report, corn prices have varied from $1.95-3.16 over the six year period from 1981 through 1986.[3] Current prices are $2.30 per bushel. The 1989 Department of Agriculture press release states that for increases in ethanol production up to about 3 billion gallons per year, each additional billion gallons would increase corn prices by about $0.08-0.28 per bushel assuming no major drought.[4]

Expanded ethanol production would have differing effects on different segments of the agriculture industry. Corn growers may experience higher incomes. Livestock producers who feed corn would experience increased costs, while those using byproduct feeds would have lower costs. It is not clearcut what will happen to soybean farmers, since corn yields about the same amount of high protein feed per acre as soybeans. Soybean producers whose land is not suitable for corn could be hurt by competition from ethanol byproducts. As long as some soybean producers can switch to corn, the soybean meal supply will decrease, thus mitigating the drop in soybean meal prices that would occur if more corn were produced without any drop in soybean production.

The 1988 Department of Agriculture report cites net corn costs (excluding the value of by-products) equivalent to $0.56 per gallon of ethanol for a six year average (1981-87) for a wet-milling plant.[3] The costs for a dry-milling plant are somewhat higher at $0.60 per gallon. This report also cites net operating costs excluding corn for ethanol plants in 1987 to be $0.47 per gallon including energy, ingredients (other than corn), personnel, maintenance, management, administration, insurance, and taxes. The cost decreases to $0.38 per gallon for a "state of the art" plant. An existing state of the art plant can therefore produce ethanol at a marginal cost of about $0.94 per gallon. The 1989 Department of Agriculture press release cited figures ranging from $0.85-1.20 per gallon.[4] The 1988 Department of Agriculture report cited the lower range of the cost to be $0.75 per gallon, but that was for a year in which byproduct prices were unusually high and corn costs were especially low (e.g., $1.40 per bushel), and neither of these conditions are expected in a scenario of greatly expanded ethanol production.[3] Current wholesale market prices for ethanol are about $1.00 to $1.20 per gallon, which translates to a cost of $1.33-1.60 per gasoline-equivalent gallon (neglecting any efficiency improvement with ethanol). Current wholesale gasoline prices are about $0.50-0.60 per gallon.

In some cases cost savings may be possible from favorable plant siting for new plants, but where ethanol plants are added to existing wet or dry mills, the savings due to use of existing corn processing facilities are much greater than those due to favorable siting (one would expect corn mills to be located near inexpensive corn anyway). Factors to consider include access to raw materials, labor availability, site cost, and availability of transportation for plant products. Also, energy prices and the ability to conserve energy (e.g., such as in process control and waste heat utilization) are very important, as are technology improvements.

New technologies having potential for commercial viability include alterations in the yeast strain used for fermentation and use of membrane technology to separate solubles, which could allow 40% of the water to be separated prior to distillation (thus reducing the energy required). Also, the constituents of the mash in an ethanol plant reportedly include many high value amino acids, fine chemicals, etc. Just as gasoline prices have been reduced by the value of petrochemical output from the same barrel of crude used to make gasoline, it is reasonable to expect that technological advances in separating these high value products from the mash might reduce net corn costs and therefore ethanol costs. However, such new technology might also be applicable to and have a cost advantage with other complex mixture feedstocks, so it is uncertain that cost reductions will occur. Furthermore, with continued research in the utilization of cellulosic fiber, this part of the corn byproducts could also be converted into a commercial product. Despite these cost reducing factors, market prices are not necessarily established by the lowest cost suppliers, so a large portion of the ethanol produced would need to take advantage of advances such as these for it to have a large impact on market price.

Estimates of the production cost from new plants built to satisfy a large expansion of fuel ethanol use are rather uncertain, in part because of the interaction with corn and byproduct prices. According to USDA analyses a 4-5 fold increase in production is estimated to increase ethanol costs by about 40%, with a minimum cost of $1.00 per gallon.[3,16] Reference [3] gives an upper range cost estimate for ethanol from new medium-large plants of average efficiency to be about $1.50 per gallon for a corn cost of $2.50 per bushel. Higher oil costs, greater demand for corn or increased supply of byproducts would tend to raise this cost, while improved plant efficiency or expanded extraction and marketing of byproducts such as human grade DDG would tend to counteract these cost increases. Based on this information, this report will assume a wholesale cost range of $1.00 to $1.50 per gallon of ethanol derived from corn.

In the past years, a number of small ethanol plants have been shut down because even with the Federal subsidy, and in some cases a state subsidy, they were not economically viable. Although capital costs of re-opening such plants are usually much less than building new plants, the small size and prior lack of viability of these plants make them irrelevant in considering future ethanol costs and supply.

3.1.1.5 Tax Subsidies

Starting in 1979, motor fuels with at least 10% denatured ethanol derived from renewable resources were exempted from the $0.04 per gallon motor fuel excise tax. At a 10% ethanol concentration this is equivalent to $0.40 per gallon of denatured ethanol itself). As an aside, since the anhydrous ethanol is denatured with gasoline, this is equivalent to 9.5% ethanol. A year later, an alternative credit of $0.40 per gallon of denatured ethanol used as a motor fuel in any concentration was established in the form of a credit against the seller's income tax. In 1983, the motor fuel tax was increased to $0.09 per gallon with the ethanol blend excise tax exemption being increased to $0.05 per gallon and then $0.06 per gallon in 1985, and the blender income tax credit accordingly increased to $0.60 per gallon. The subsidy as a credit against income tax is scheduled to expire at the end of 1992, while the exemption from motor fuel taxes expires September 30, 1993. Congress and others have discussed extension of these subsidies.

Even assuming that the high ethanol level fuels considered in this report would be treated as gasoline by the U.S. Treasury, the $0.06 per gallon excise tax exemption would not provide much benefit on a per-gallon of ethanol basis. Instead of $0.60 per gallon at 10% ethanol, it would only be worth about $0.07 per gallon of ethanol in E85. Even complete exemption from the excise tax would not be much help. Therefore, the blender income tax credit would be the subsidy used at high ethanol levels because it provides the subsidy of $0.60 per gallon of ethanol regardless of the ethanol content of the fuel.

Other Federal subsidies for ethanol production have been provided at times in the form of special investment tax credits and loan guarantees. Also, many states provide subsidies in the form of partial or total exemption of gasohol from their own motor fuel taxes or in the form of production credits or payments; about 20 states provide subsidies averaging $0.20-0.30 per gallon of ethanol and totalling roughly $160 million per year.

These subsidies for ethanol can have a substantial effect on the Federal budget and on state budgets where it is subsidized. These effects are discussed more fully in section 3.6. Without the Federal and state subsidies, neat ethanol from corn would not be competitive with gasoline at its current and projected prices.

3.1.2 Ethanol Production From Natural Gas and Petroleum

Although virtually all the ethanol for fuel use in the U.S. currently comes from fermentation of grain (domestic ethanol) or other sugar crops (imported ethanol), ethanol can also be, and is now, produced from petroleum and natural gas via an ethylene (C_2H_4) intermediate step. This conversion of ethylene to ethanol is done by hydration of ethylene, in which water vapor is added to ethylene vapor in the presence of an acid catalyst. As with the fermentation approach, this process yields ethanol with about 5% water which then can be removed with a dehydration step, but for many industrial purposes this final dehydration is unnecessary.

There are many non-beverage and non-fuel products that make use of ethylene-derived ethanol including food extracts, toiletries, pharmaceuticals, solvents, and cleaning products. Ethanol that is derived from petroleum or natural gas sources does not qualify for the income tax credit or the excise tax exemption. Also, ethanol that is to be used for other than fuel purposes does not qualify for these tax subsidies. Therefore, for these industrial uses ethanol from petroleum sources competes directly with ethanol from grain. However, since the chemical companies producing ethanol from petroleum products are often part of the same petroleum company supplying the ethylene feedstock, it is usually most economical for the ethanol for these uses to be produced by the ethylene route. A rough estimate of the cost of ethanol derived from ethylene is $1.20-1.50 per gallon.[11]

Other competing uses of ethylene include use as an anesthetic, as a fuel with oxygen for high-temperature flames, and as a coloring and ripening agent for citrus fruits and tomatoes. In addition to these direct uses of ethylene, it is a very important petrochemical feedstock, both in terms of quantities used and economic value. For example, it is the feedstock for ethylene oxide, ethylbenzene, ethyl chloride, ethylene dichloride, ethylene glycol (for anti-freeze), and polyethylene, most of which are used to produce hundreds of other end products. The free world consumption of ethylene is estimated to be about 40 billion pounds per year.[17] A mere 6% of this would fuel a million vehicles if it were converted to ethanol.

Ethylene is most cheaply produced by reduction or steam cracking of ethane or propane recovered from natural gas, or from the volatile fractions of petroleum. Excess butane from gasoline RVP reductions could also be processed into ethylene. However, due to the high demand for ethylene, many producers have been turning to heavier petroleum fractions, such as gas oils, as feedstocks.

It should also be practical to make ethanol from direct oxidation of ethane using process technologies similar to those used to make methanol from methane in natural gas. The ethane could be taken from natural gas produced in this or other countries. However, ethane feedstock value in other markets would affect the costs, and ethane is usually less than 10% of natural gas. If there were no nearby market for the methane, it would probably not be economical to invest the capital to separate out the ethane and convert it to ethylene and ethanol.

Also, it may be possible to oxidize natural gas liquids directly to various alcohols slanting the process to form ethanol. Other alcohols made could possibly be removed. Furthermore, intensive research is underway for direct catalytic oxidative conversion of methane to ethylene, which could then be hydrated to ethanol. Although promising results have been obtained with this process, it is too early to determine if these can be improved to industrially attractive levels.[18]

3.1.3 Non-Food Biomass

As introduction, various feedstocks other than corn have been considered for ethanol production. These include potatoes, sweet potatoes, Jerusalem artichokes, sugar beets, fodder beets, sweet sorghum, and grains other than corn. Should corn prices rise, these other crops might be a less expensive feedstock because they can be grown on a broader range of lands and climates. Also, non-food biomass sources such as cellulosic biomass could be expected to allow greater amounts of ethanol to be produced than relying only on the corn crop.[12]

Many advances have come out of continuing research on processes to break down the various types of cellulosic biomass into sugars that can then be fermented. For example, the large scale production of ethanol from lignocellulosic feedstocks is considered a possibility for the future (e.g., in the timeframe of 2000-2010 depending on research funding, oil prices, etc.).[12] Lignocellulose comes from sources such as trees, grass, waste paper, and cardboard which are relatively inexpensive and plentiful as raw materials.

Some cost estimates have been made for using cellulose including the energy value of unconverted cellulose as a byproduct. The current cost estimate for ethanol from cellulose at the wholesale level is roughly $1.35 per gallon [19] compared to $1.00-1.20 per gallon from fermentation in a grain plant at current corn prices. According to the 1988 Department of Agriculture report cellulose conversion would be cost competitive with corn based production without further technological advancements if corn prices were to increase to $3.50-$4.00 per bushel.[3]

The Department of Agriculture report also states that research on a number of areas would be useful.[3] One area is investigating processes to readily convert biomass materials into processed cellulose, lignin, hemicellulose, and coproduct streams. Another is chemical modification of cellulosic materials to products which can be easily used for fuel type applications. In general, the biotechnology for production and conversion of cellulose to ethanol is fairly immature with much optimization still to be done, whereas the technology of fermenting corn into ethanol is quite mature with much smaller additional improvements likely.

Estimates of the future cost of ethanol from cellulosic feedstocks are optimistic based on expected advancements in conversion efficiency including customizing bacteria and/or yeasts using genetic engineering techniques. DOE has ongoing research that may eventually provide improved technology for the conversion of biomass to ethanol. This research is working toward a long-term future goal of producing ethanol for $0.60 per gallon (plant gate cost, including capital recovery) without government subsidies. This goal is based on reducing feedstock costs from $3.00-3.25 per dry ton to $2.00 per ton. This depends on research success to improve average wood yields on selected test sites to 9-12 dry tons per acre per year from the approximate 7 tons per acre currently achievable. In addition, it depends on research to improve crop genetics and large-scale cultivation. While the long-term future cost of ethanol using these new technologies is highly uncertain, DOE is confident that research will result in significant cost reductions compared to the current cost of using cellulosic resources to produce ethnol, which is about $1.35 per gallon. DOE is continuing to work on future technologies that will improve the yield rate, the rate and concentration of the ethanol process, and lower the enzyme cost through biotechnology, as well as on system optimization and scale-up testing.[19,20]

Another issue with ethanol from cellulosic materials is the theoretical potential quantity available. While the potential supply of ethanol from corn has been very roughly estimated at 10% of the U.S. gasoline requirements, the use of cellulosic biomass has the potential to replace much or all of the gasoline consumption in the U.S.[19,21,22] An average of 328 million acres of cropland are planted each year for food crops.[19] Replacement of all the gasoline consumption would involve use of 192 million acres of other cropland currently in various production reduction, conservation, and soil erosion prevention programs sponsored by the government; land for which new crops will be needed; and pasture, range, and forest lands that are capable of supporting crop production. The economic costs of this theoretical option are not known but could be several times that of gasoline. Also, such an approach on a large scale is vulnerable to wide swings in production due to weather variations unless buffered by stockpiles.

In addition to increasing the ethanol supply potential (at what may be a high cost), cellulosic materials could be used to produce animal feed. In the late 1970's there were several technologies available to convert cellulose and hemicellulose into an ruminant animal feeding ration that had a much higher carbohydrate to protein ratio than DDG or gluten feed from grain. In certain limited circumstances economic and environmental factors may favor using corn or other grains for the production of ethanol and then using partially hydrolyzed lignocellulose to replace the needed carbohydrate energy to balance the feeding ration.[23]

Ethanol from cellulosic biomass also has advantages over corn in terms of the agricultural energy inputs required. This is discussed in section 4.3 in connection with the greenhouse effect and carbon dioxide production.

3.2 Imports

One aspect of ethanol as a motor vehicle fuel that is a key attraction to some proponents is that it can be produced domestically. Current domestic ethanol production for fuel of 840 million gallons per year displaces about 40,000 barrels per day oil equivalent or 0.2% of total U.S. crude consumption, not taking into account the energy consumed in growing the corn and converting it into ethanol. This small amount has no noticeable effect on U.S. energy security. Despite the expandable domestic production capability, it may be desirable at some point to admit overseas ethanol depending on demand, domestic capacity, and cost factors. This would most likely involve reducing the tariff to allow imported ethanol to be competitive with domestic ethanol, thereby authorizing U.S. tax subsidies to other countries.

As discussed earlier in the section on fermentation from grain, there may be some relatively high limit of domestic ethanol production from grain beyond which food prices could increase significantly. Such a high production level would probably also be more than enough to satisfy any reasonable goal for agricultural sector and rural economy stimulation. If it is desirable to have even greater volumes of ethanol used, for example because of global warming effects or other air pollution benefits, overseas sources could be considered. Temporary reliance on some overseas ethanol could also allow U.S. consumption of ethanol to exceed domestic production during the period needed to bring more grain fermentation plants on line, during droughts, or during the longer period until production from non-food biomass becomes economical as a result of a research and development effort. Foreign producers may be unwilling to make the substantial capital investments required to export ethanol to the U.S. only during droughts that occur every five years or so. Imports for any reason could also have adverse impacts on the balance of payments and the Federal budget as the cost of ethanol subsidies would increase.

The only country other than the U.S. with a significant ethanol fuel industry is Brazil, where ethanol is made from sugar cane. Brazil's annual production is about 5 billion gallons per year, or about six times current U.S. production.[12] Much of this ethanol is hydrous which would have to be dehydrated if the U.S. market were based on anhydrous ethanol, but there is also a substantial amount of anhydrous ethanol produced for gasoline blending. Due to the large amount of tillable land that is not under cultivation, Brazil could expand the acreage devoted to sugar cane and ethanol considerably while causing little or no food price increases. In recent years Brazil has placed more priority on developing its oil resources and production because it is lower cost than ethanol. Brazil also has some flexibility to substitute petroleum for ethanol for domestic consumption, thereby releasing ethanol for export. Ethanol production and pricing are heavily subsidized by the Brazilian government and the program has been costly to Brazil. Also, Brazil is currently importing ethanol to meet its domestic demand while it takes advantage of high world sugar prices and, therefore, is not in a position to export ethanol to the U.S.

Some Caribbean Basin nations are in a situation somewhat similar to Brazil's in that sugar cane is a suitable crop for their land and climate. Furthermore, they benefit from a very limited exemption from the 60 cent per gallon ethanol tariff. (This exemption appears more politically secure for ethanol produced from local feedstocks than for foreign ethanol that is merely upgraded in the Basin.) However, their ability to expand cane acreage is much less than Brazil's and their ethanol production capacity is presently small, but is expanding.

Wine-derived ethanol from European countries is another possible source of imports. Due to the agricultural support programs, some European nations have accumulated stocks of surplus wine and of partially refined wine ethanol. This ethanol in effect will be sold to the highest bidders, irrespective of its production cost. The current stock is about 400 million gallons, or about one-half the annual U.S. production rate. However, the sustainable excess production is reportedly only about 100 million gallons per year, too little to affect a U.S. market much. Moreover, the wine-derived ethanol requires more expensive upgrading to remove impurities than corn or sugar cane-derived product. Also, Europe is considering adopting an ethanol fuels program, and costs of producing ethanol from agricultural feedstocks in Europe are higher than in the U.S., so Europe may not be a feasible source for imported ethanol. Finally, with imported ethanol, the U.S. Government would be in effect subsidizing European farmers while attempting through GATT to gain agreement with European producers to phase down subsidies.

There may be other regions of the world where sugar cane, corn, or other grain could be grown and fermented to satisfy a U.S. ethanol fuel market. Presently, the U.S. produces incremental corn as cheaply as any other nation, and it is not possible for another nation to produce and deliver ethanol to the U.S. at a competitive price without a subsidy.

If the technology for ethanol production from cellulosic biomass develops sufficiently to allow domestic production through this route instead of or alongside production from corn (whose price may have been pushed up by increased ethanol demand), the potential for imports may also expand. While the U.S. might be able to produce sufficient biomass to meet a given requirement for ethanol, other nations may have a natural competitive advantage for sustained production due to factors such as longer growing season and more optimum rainfall. It is difficult to predict which regions will be most efficient at growing new types of non-food crops. Some other nations might compete temporarily as they deplete their present biomass cover, for example tropical rainforests, although there has been no indication of plans for production of ethanol from cellulosic materials in such areas.

If ethanol from fossil-fuel ethylene becomes a significant source, it is likely that overseas producers will have a cost advantage over domestic producers. An exception might be domestic production from specific hydrocarbon fractions that otherwise would have low market value. For example, surplus butane might be converted to ethylene and then ethanol.

U.S. trade policy obviously will influence whether overseas ethanol actually enters the U.S. The existing $0.60 per gallon tariff, whose purpose is to prevent importers from benefiting from the $0.60 per gallon Federal subsidy, makes import uncompetitive except for those that qualify for an exemption, as in the Caribbean Basin case.

3.3 Transportation and Marketing Costs

3.3.1 Delivery to Terminal or Bulk Plant

Most of the ethanol in the U.S. is produced in the central part of the country close to farm states as shown in available 1987 production figures. About 50 commercial-scale plants currently produce ethanol from grain; the plants range in size from 500,000 to 255,000,000 gallons per year. Even a 255 million gallon ethanol plant is small compared to a modern refinery, which can have an annual output well over 2,000 million gallons of refined product per year. The plants are located in about 20 states, many of which are in the farming sections of the central part of the United States.[2] If ethanol production increases in the future, it will likely be through addition of more plants of the largest size. They will likely be geographically situated to minimize grain or biomass shipment costs to the extent compatible with other economic factors.

It is estimated that it presently costs $0.06 per gallon for gasoline shipment as a national average or $0.03 per gallon for shipment to the the nine worst ozone non-attainment areas (these figures include both long range and local distribution). The lower cost is due to the proximity of the non-attainment areas to major ports and pipelines. The projected figure for methanol given in the September 1989 EPA methanol report is about $0.03 per gallon.[24]

Ethanol is now shipped by rail car or truck for further blending. The current production (about 840 million gallons annually) represents about 0.8% of gasoline production in the country as a whole (or 0.5% on an energy equivalent basis); however, some portions of the country such as Illinois have a much higher market share (e.g., about 3% ethanol which represents about 30% gasohol) compared to the average. These states provide an ethanol subsidy in addition to the Federal subsidy. If neat or near-neat ethanol is primarily used as a fuel in areas with severe ozone problems the nearest high-ozone market for ethanol fuel would be the Chicago-Milwaukee region. This region would also be the most expensive for shipping imported methanol. An ethanol vehicle sales fraction of about 15% in the Chicago-Milwaukee region would eventually consume the current U.S. production of ethanol, after full fleet turnover. Significant E85 or E100 sales in other high ozone areas would require much more of it to be transported from the Midwest to the East, West, and Texas coasts than is now occurring with ethanol.

Currently, in the U.S. ethanol is not shipped at all by pipeline, which is the least expensive mode of transport. Thus, in the short term the cost of shipping larger volumes of ethanol (presumably by rail car or barge) will be greater possibly by several cents per gallon than that for gasoline but probably no more than the current cost of shipping ethanol.[25]

Although it is not the current practice, alcohols should also be able to be shipped in pipelines provided steps are taken to assure pipeline cleanliness (to prevent fuel contamination) and to eliminate excess water in the pipeline system to prevent phase separation. As mentioned in section 3.1.1.3, this is already done in Brazil.[9] In general, ethanol plants in the Midwest are located near certain pipeline routes which run from Texas and Oklahoma though the Midwest to the East, but not to the West. In the long-term, a system of new connector type pipelines would be needed to connect to the long distance pipelines serving new ethanol markets outside the farm states. However, due to costs such as for system preparation and maintenance, shipment in a multi-product pipeline may not have the significant cost advantages for alcohols that it has for petroleum products.

One cost savings advantage in the distribution of ethanol is that ethanol fuel would be a fungible product. Fungibility is the ability to mix or interchange products from two sources, as in the case of shipments through a pipeline, without having a purchaser-discernible effect on the products. Currently, gasoline may or may not be fungible, depending on whether it meets certain specifications set by pipelines. Crude oil is usually not fungible unless it comes from the same field, because of the large chemical differences which exist between the various types of crude oil. Ethanol production yields a virtually pure single compound (or ethanol with water in the case of hydrous ethanol). Once exact specifications for fuel grade ethanol (E85 or E100) have been determined, it is unlikely that pipelines would place any additional specifications on the fuel since it is so uniform a product. Thus, for pipelines and other distribution systems, ethanol should be a very fungible product.

Besides pipelines, other points in the distribution system that would require some attention are the storage tanks at terminals and service stations. If tanks are used that have been used for gasoline, they would in many cases need to be cleaned out of water and any buildup of scale, or else the solvent properties of the ethanol could result in fuel contamination. This has been a standard practice for many marketers of gasohol, so it is not expected to present any problems to do it for E85 or E100.

3.3.2 Distribution to Consumers

Other than the need for segregation from gasoline, the major factor affecting distribution of ethanol to consumers would be the increased amount of ethanol needed due to its lower energy content per gallon compared to gasoline. The actual quantity of ethanol needed is determined by the relative fuel economy (in miles per gallon) of an ethanol fueled vehicle compared to gasoline, which depends not only on the energy content of the fuel, but also on the vehicle efficiency in converting that energy into useful work.

Ethanol has about 67% of the energy content of gasoline (76,000 versus approximately 114,000 BTU per gallon). In a vehicle designed to take advantage of the properties of ethanol (e.g., higher octane allowing higher compression ratio, leaner combustion, higher post-combustion pressure, greater thermal and volumetric efficiency) neat or near-neat ethanol is expected to result in an efficiency benefit compared to gasoline. Although one might expect the efficiency benefit to be slightly less with ethanol than methanol due to its chemical structure being in between those of gasoline and methanol, an E100 vehicle has advantages that tend to balance out these disadvantages. For instance, as the air-fuel ratio is decreased from stoichiometric to obtain optimum efficiency, ethanol theoretically loses less of its post-combustion pressure benefit than methanol. Also, since ethanol has a greater energy density (BTU per gallon) than methanol, the fuel tank can be smaller and the vehicle weight slightly less, allowing slightly better fuel energy economy. In the case of an FFV operating on E85, many of these advantages are sacrificed to maintain compatibility with straight gasoline, so the benefit would be about half as much as with an FFV operating on M85. Reference [26], provided as Appendix D, contains a full discussion of these and other factors affecting ethanol efficiency.

While there are currently no test data and no measurements for improved efficiency for highly optimized neat or near-neat ethanol vehicles, testing with methanol has led to estimates of 30% efficiency improvement with neat methanol in a dedicated methanol vehicle and about 5% with 85% methanol in an FFV. (Ford estimates an efficiency improvement of only 15%-20% rather than 30%.) The 30% figure represents vehicle as well as engine redesign conditions, but we know of no reasons why it could not be achieved if one were to design a truly optimized E100 (or M100) vehicle, which no one has done yet. Furthermore, some limited test data from moderately optimized neat ethanol vehicles in Brazil also support a projected 30% efficiency improvement potential for E100.[27] It should be noted that the 30% estimate does not include any credit for exhaust heat recovery, flywheels, super light vehicles, etc., since these efficiency improving techniques could also be used with gasoline vehicles.

Thus, for the purposes of this report, the efficiency improvements with ethanol are estimated at about 30% for neat ethanol in a dedicated vehicle and 2.5% for near-neat (e.g., 85%) ethanol in an FFV. Combining this with the 67% factor gives an overall fuel economy (miles per gallon) for a vehicle fueled with 100% ethanol of 87% that of a gasoline vehicle. The number would be 72% for a vehicle using 85% ethanol. This means that one needs about 15-39% more ethanol than gasoline on a gallon per mile basis.

Based on this increased fuel volume for a given number of vehicle miles traveled, one can infer that an increased rate of fuel drop-offs at retail service stations would be needed. (In general, larger underground storage tanks would not be a solution, since these tanks are usually at least as large as the tank trucks making the deliveries.) An increased drop-off rate implies an increased number of tank trucks and drivers to transport the fuel from the storage tankage to the service station. Assuming not all stations would carry ethanol fuel, some of this increase in trucks and drivers could be offset by optimizing truck delivery routes for delivery only to the ethanol stations. Some of the costs associated with these changes have been analyzed for methanol in Reference [28]. For methanol, the cost of the increased number of trucks is estimated to add $0.0019-0.0039 to the cost of each gallon. Since the quantity of ethanol required would be 33% less than that for methanol, a rough estimate of the added truck costs would be $0.0013-0.0026. However, these estimates do not include other related costs such as labor or truck operating costs. As a base case, the total cost of delivering gasoline less than 100 miles is between $0.01 and $0.02 per gallon.

To be able to provide for fuel ethanol segregation from gasoline, and provide for increased drop-off rates relative to gasoline, one may need increased storage tankage (e.g., in tank farms) above what is currently used for gasoline. Naturally, any such changes in the distribution system depend largely on the percent of vehicles using the neat or near-neat ethanol and the percent of service stations carrying this fuel.

Another possible change associated with increased fuel volume is the dispensing pump flow rate. If larger vehicle fuel tanks are used to maintain a range comparable to gasoline, higher flow rate pumps might be needed to keep the average time for a fill-up from increasing. However, it may be found that this is not important relative to the total time spent by consumers at the station when refueling.

3.4 Vehicle Hardware Costs

Use of an optimized vehicle fueled with neat (or less so with near-neat) ethanol should allow use of a smaller, lighter engine which delivers the same power as the gasoline-fueled engine it replaces. The weight saved in the lighter engine means that portions of the body structure and the suspension can be made lighter, especially if the engine/vehicle design is done as an entire system. The resulting vehicle will have equivalent power and weigh less than the vehicle it replaces; hence, the resulting vehicle will have better performance. The improved performance means that even further weight reductions are possible if the engine is resized for equivalent performance. The smaller engine will allow powertrain weight and cost savings because the power transmitted will be reduced.

The smaller engine size should lead to a smaller catalytic converter since most emission control systems use a certain ratio of catalyst volume to engine displacement. Also, the lower vapor pressure of ethanol compared to gasoline should result in savings in the evaporative control system.

Ethanol's combustion properties should be similar to those of methanol which result in less heat being rejected into the engine's cooling system. The lower heat rejection and the cooler exhaust leads to more savings. The neat ethanol fueled engine will have to increase the sensible heat in the exhaust. This will require exhaust port insulation which provides the appropriate exhaust conditions for effective emission control. The fact that not as much heat is rejected into the vehicle's cooling system means that a smaller radiator can be used.

However, fuel system modifications for neat or near-neat ethanol might lead to cost and weight increases. Hydrous neat ethanol (95% ethanol and 5% water) vehicles may need more attention to material selection since this fuel has somewhat greater rust forming tendencies than the anhydrous neat ethanol. It is expected that any material changes implemented for methanol vehicles would also be sufficient for ethanol vehicles.

Cold starting with neat ethanol at low temperatures would require similar solutions as used with neat methanol due to the similarly low volatility of ethanol. For instance, some existing ethanol and methanol vehicles have used a separate fuel system with a more volatile fuel (e.g., gasoline or propane) for starting and then switching to the alcohol. Also, with enough lead time, engine hardware will probably be developed such as a sophisticated direct fuel injection system to assure cold starting [29,30]. The more sophisticated fuel injection systems required for satisfactory cold start performance with neat ethanol may be more expensive than that needed for a gasoline vehicle. Also, as with methanol, the larger fuel tank than for a gasoline vehicle will be more expensive and may need modifications such as a flame arrester or bladder for safety. However, the fuel tank size for ethanol would not need to be as large as for methanol due to ethanol's greater energy density.

On an overall basis, there are several areas where cost savings and increases are expected. While there is uncertainty on the costs of vehicles designed for neat ethanol, and higher costs have been estimated by others such as Ford and GM, this report assumes that in the long term the savings and increases will balance out with no overall cost difference between future optimized neat ethanol vehicles and gasoline vehicles. It should be noted that since some of the changes needed for a fully optimized vehicle (e.g., the structural weight savings) could only be realized with the design of a totally new vehicle, achieving the full efficiency potential of ethanol (or methanol) fuel would require a lead time of at least 5-6 years. As long as ethanol vehicles are simply modifications of their gasoline fueled counterparts as in Brazil, the full benefit of potential weight reductions will not be possible.

For a flexible fuel vehicle operating on various fractions of gasoline and ethanol, one does not have all the cost savings possible with a neat ethanol fueled vehicle. Also, a fuel sensor is required. EPA is relying on the Ford cost estimates of an extra $150 to $300 for a flexible fuel methanol vehicle produced at high volumes; the Ford numbers were recently updated to come up with this new range which is slightly lower than the old numbers.[31,32] An average cost of $300 per vehicle (the high end of the range) will be assumed.

3.5 Vehicle Operating Costs

The only difference in operating costs between ethanol and methanol vehicles is expected to be the fuel cost. Table 3-2 provides a fuel cost breakdown for ethanol relative to gasoline. For gasoline a terminal price of $0.69 is used corresponding to current crude oil prices of roughly $20 per barrel. For comparison a gasoline price of $1.07 per gallon is shown, corresponding to a crude oil price of about $35 per barrel. These are the same gasoline prices used in the methanol report. The ethanol plant gate price range of $1.00 to $1.50 per gallon was chosen to bracket current prices of about $1.00-1.20 per gallon and account for price increases associated with greatly increased production, as described in section 3.1.1.4. If crude oil prices also increase substantially in the future, the high ethanol cost may increase beyond $1.50 per gallon due to the use of petroleum products in corn farming/transport. A column is also included to show a possible future cost of ethanol derived from cellulosic biomass, as described in section 3.1.3. The dealer markup numbers for ethanol are based on maintaining constant total profit while increasing throughput of ethanol (due to lower energy content than gasoline).

Table 3-3 shows the gasoline-equivalent ethanol retail price range for three different ethanol vehicle scenarios for the high, low, and future biomass ethanol prices mentioned in the previous paragraph. The gasoline-equivalent ratio is derived from the ratio of the energy content of gasoline to that of ethanol (1.5) adjusted for possible efficiency differences. The greatest efficiency improvement comes from an E100 vehicle optimized for ethanol use. Prices for corn-derived ethanol are shown both with and without a $0.60 per gallon ethanol tax subsidy. The future biomass ethanol prices are only shown without a subsidy since no subsidy is anticipated in that scenario.

Using the above ethanol and gasoline prices, Table 3-4 compares the annual fuel costs for ethanol relative to gasoline assuming accumulation of 10,000 miles per year and 27.5 gasoline-equivalent miles per gallon. Ethanol costs are shown to be either higher or lower than gasoline costs depending on the specific scenario.

Table 3-2

Total Pump Price Comparison for E100 without Subsidy
($ per gallon)

	Low Crude ($20/bbl) Gasoline	Current Low Cost Ethanol	High Cost Ethanol[a]	High Crude ($30/bbl) Gasoline[a]
Terminal or Plant-Gate Price	0.69	1.00	1.50	1.07
Long Range and Local Distribution	0.06(0.03)[b]	0.06[c]	0.06[c]	0.06(0.03)
Service Station Markup[d]	0.09	0.06-0.08	0.06-0.08	0.09
All Taxes	0.24	0.16	0.16	0.24
Subtotal Distribution	0.39(0.36)	0.28-0.30	0.28-0.30	0.39(0.36)
Total Pump Price	1.08 (1.05)	1.28-1.30	1.78-1.80	1.46 (1.43)
Per Gallon Gasoline Equivalent:				
- 30% Ethanol Improvement	1.08 (1.05)	1.48-1.50[e]	2.05-2.08	1.46 (1.43)

(For the case of E85 with 2.5% improvement, see next table, since the cost of the 15% gasoline must be included.)

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a) The high ethanol case is based on increased corn price due to greatly increased demand for ethanol. If crude oil prices also increase substantially in the future, the high ethanol cost may increase beyond that shown due to the use of petroleum products in corn farming/transport.

b) Numbers in parentheses are for gasoline shipped to U.S. non-attainment areas on coasts or on major water or pipeline routes.

c) Shipping cost of ethanol assumes large enough quantities that no premium would be applied relative to gasoline for identical shipping modes (e.g., barge or truck), and that there would be sufficient incentive for pipeline companies to make the necessary accommodations to ship ethanol to the applicable areas.

d) These estimated costs of service station markup assume that gasoline retailers would require a lower markup per gallon of ethanol sold than a gallon of gasoline, due to the lower energy content of ethanol and subsequent increased volume of ethanool sales relative to gasoline on a system wide basis.

e) 1.5 (BTU ratio)/1.3 (efficiency ratio) = 1.154
1.154 x $1.28 = $1.48

Table 3-3

Gasoline-Equivalent Ethanol Retail Price
($ per gallon except as noted)

	E100, No Credit For Efficiency	E85 2.5% Better Efficiency	E100 30% Better Efficiency
Ethanol Plant Gate Price	1.00-1.50	1.00-1.50	1.00-1.50
Gasoline Blending for E85	0	-0.05 to -0.12[a]	0
Distribution, Markup and Taxes[b]	0.28-0.30	0.30-0.31[c]	0.28-0.30
Total Ethanol Retail Price	1.28-1.80	1.25-1.69	1.28-1.80
-$0.60/gal tax credit on EtOH portion[d]	0.68-1.20	0.74-1.18[e]	0.68-1.20
Gasoline-Equivalent Ratio[f]	1.50	1.39[g]	1.154[h]
Total Gasoline-Equivalent Ethanol Retail Price	1.92-2.70	1.74-2.35	1.48-2.08
-$0.60/gal tax credit on EtOH portion[d]	1.02-1.80	1.03-1.64	0.78-1.38

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a) Cost of 0.15 gallons of gasoline @$0.69 per gallon minus 0.15 gallons of ethanol @$1.00-1.50 per gallon.

b) Without any tax subsidy. These estimated costs of service station markup assume that gasoline retailers would require a lower markup per gallon of ethanol sold than a gallon of gasoline, due to the lower energy content of ethanol and subsequent increased volume of ethanool sales relative to gasoline on a system wide basis.

c) 0.85($0.28) + 0.15($0.39) = $0.30

d) Reflects retail fuel price only; $0.60/gallon cost must still come out of government budget and be borne by taxpayers in general.

e) $1.25-0.85($0.60) = $0.74

f) (BTU/gallon gasoline)/(BTU/gallon ethanol fuel) adjusted for efficiency improvements.

g) 0.85(1.5)/1.025 + 0.15/1.025 = 1.39

h) 1.5/1.30 = 1.154

Table 3-4

Annual Fuel Costs[a]

Gasoline		$0.60/gal	E85		E100	
Low	High	Subsidy	Low	High	Low	High
$382	$520	No	$633	$855	$535	$753
$382	$520	Yes	$327	$553	$284	$502

Change Relative To	$0.60/gal Subsidy	E85 Low	E85 High	E100 Low	E100 High
Gasoline Low	No	+66%	+124%	+40%	+97%
	Yes	-14%	+ 45%	-26%	+31%
Gasoline High	No	+22%	+64%	+3%	+45%
	Yes	-37%	+ 6%	-45%	- 4%

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a) Gasoline-equivalent assuming 10,000 miles/year and 27.5 MPG

3.6 Budget Costs of Ethanol

If a large ethanol program as envisioned in this report is implemented, and if the current Federal and state subsidies are extended long enough to apply during such a program, there would be very large budget effects on a Federal level and in certain states. At current ethanol production levels the Federal subsidy costs the Highway and Mass Transit Trust Fund roughly $500 million per year, which means that much less money for highway construction and repair (since Fund outlays would decrease automatically). If this quantity of ethanol is increased by a factor of 4 or 5, the Federal cost would be $2.0-2.5 billion. Since this would mostly result from the blenders income tax credit rather than the excise tax exemption, it would not further reduce the Highway and Mass Transit Trust Fund but would reduce General Fund tax revenues thus increasing the Federal deficit unless compensating tax increases are enacted.

The issue of state budget effects is less clear due to the range of tax subsidies, which fuels they apply to, and whether a given state contains a major ozone non-attainment area where the ethanol vehicles would be used. About 20 states now provide subsidies averaging $0.20-0.30 per gallon of ethanol and totalling roughly $160 million per year. Currently, only two of the nine ozone non-attainment areas in the President's proposal have state ethanol tax subsidies. These are Illinois, which has a 2 percent tax exemption, and Connecticut, where the subsidy is $0.01 per gallon of 10% ethanol blend (equivalent to $0.10 per gallon of ethanol).

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4.0 ENVIRONMENTAL ANALYSIS OF ETHANOL

The major effects of neat or near-neat ethanol vehicle use are expected to be in the area of ozone formation and air toxics. Using current vehicle emission control technology, NOx and CO emissions can be equivalent to gasoline vehicle levels. There is no reason to expect or require them to be better, since vehicles meeting the applicable NOx emission standards are adequate for general attainment of the NO_2 standards, and unlike CNG ethanol has no particular advantage with respect to CO emissions.

4.1 Urban Ozone and Pan Level

Ethanol-fueled vehicles tend to emit more ethanol and acetaldehyde than a similarly configured gasoline-fueled vehicle. Formaldehyde emissions are also expected to increase relative to a gasoline-fueled vehicle but not to as great an extent.[1] Compared to a methanol-fueled vehicle, a vehicle run on ethanol is expected to emit less formaldehyde and essentially no methanol, but more ethanol and acetaldehyde.

Non-methane hydrocarbon (NMHC) speciation data for ethanol-fueled vehicles are limited to one study.[1] The test vehicles were not specifically designed to run on ethanol. Data were obtained with the vehicles operating on E85 and E95. Data were also obtained with the same vehicles operating on Indolene, M100, and M85. It does not appear that the methanol and ethanol-blended fuels were matched for volatility. With these limitations in mind, the mix of NMHC emissions from the gasoline, methanol blends, and ethanol blends are not dramatically different. The ethanol-fueled vehicles tend to emit more two carbon compounds such as ethane and ethene, but less of other paraffins.

The impact of the use of ethanol-fueled vehicles on urban ozone has not yet been adequately studied. Although methanol-fueled vehicles have been studied in some detail, no quantitative modeling studies of any U.S. city exist involving the use of 85-100% ethanol in vehicles. Without a broad set of such studies, the reactivity of emissions from an ethanol-fueled vehicle relative to a gasoline-fueled vehicle can only be estimated in a crude fashion by comparing the reactivities of major emission components.

The reaction of compounds in the atmosphere with the hydroxyl radical is often used as one measure of reactivity. Table 4-1 gives hydroxyl rate constants for some of the major components in methanol and ethanol exhaust, normalized to gasoline NMHC.[2,3] (Hydroxyl rate constants strictly speaking apply only to pure compounds. The rate constant for gasoline NMHC used in Table 4-1 is actually a weighted average of the large number of pure compounds that occur in gasoline vehicle emissions.)[1] This simple approach assumes that ozone production is based solely on the rate constant for the

Table 4-1

Reactivities Per Carbon[*]

Compound	Based on OH Rate Constant[**]	Based on Relative Reactivity[***]
Ethanol	0.21	0.76-0.87
Methanol	0.13	0.69
Formaldehyde	1.30	2.31-3.72
Acetaldehyde	1.15	1.70-3.31
Gasoline NMHC	1.0	1.00

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[*] Normalized to gasoline NMHC carbon for easier comparison.

[**] The OH rate constant for gasoline NMHC is 10.16×10^3 $ppmC^{-1}min^{-1}$.[1] The relative hydroxyl rate constants are only included here because it is a simple approach often used as a measure of reactivity when modeling data do not exist. Due to the numerous limitations cited in the text and the availability of relative reactivities, this approach is not used to estimate the ozone-forming potential of ethanol-fueled vehicles.

[***] The relative reactivities of ethanol, methanol, formaldehyde, and acetaldehyde were taken from Tables 4a and 4b in reference [7]. Relative reactivities at a $NMHC/NO_x$ ratio of 8 were used since the ozone maximum occurs nearest this ratio. The ranges account for consideration of both the low and high dilution cases. In reference [7], the relative reactivities of five mixtures were calculated: 1) NMHC, formaldehyde and acetaldehyde, 2) ethane, formaldehyde and acetaldehyde, 3) propane, formaldehyde and acetaldehyde, 4) methanol, formaldehyde and acetaldehyde, and 5) ethanol, acetaldehyde and formaldehyde. The relative reactivities of formaldehyde and acetaldehyde varied depending on the co-substituted NMHC species. The relative reactivities of formaldehyde and acetaldehyde with NMHC, methanol, and ethanol as the co-substituted NMHC species were selected for this table.

reaction of each compound with the hydroxyl radical. This approach does not consider several important factors which affect ozone formation, such as reactions with species other than the hydroxyl radical, secondary reactions, photolysis, and the type of environment into which the compounds are emitted. Due to these limitations, this approach will not be considered further in this report.

A second approach, in the absence of city-specific modeling data, is to calculate the incremental reactivity of the compounds. Incremental reactivity is defined as the effects on ozone formation and NO oxidation caused by addition of the pure organic compound to a hydrocarbon surrogate-NO_x mixture. The incremental reactivity approach is applicable only to small changes in the amount of organic added to the base surrogate mixture. A photochemical trajectory model with a detailed chemical mechanism has been used to calculate the incremental reactivity of pure organic compounds as a function of VOC/NO_x ratios. Incremental reactivities have been calculated for many pure compounds, methanol, ethanol, formaldehyde, and acetaldehyde using the EKMA model over a range of VOC/NO_x ratios and initial conditions, examining both one-day and two-day episodes.[2]

A third approach is to calculate the relative reactivity of the compounds. Like incremental reactivities, relative reactivities have been calculated using the EKMA model with various detailed chemical mechanisms. The relative reactivity method, however, assesses the effects on ozone formation caused by substitution of the pure organic compound or organic mixture for a portion of the base surrogate mixture. The relative reactivity method, therefore, may be used to assess substantial changes in organic emissions. The relative reactivity method is also capable of looking at the effects of substitution of a mixture of organics. EPA in 1988 used this approach to evaluate the ozone-forming potential of organic emissions from methanol-fueled vehicles relative to typical NMHC from gasoline-fueled vehicles. Relative reactivities for methanol and formaldehyde were based on modeling results for a number of cities.[4,5] Ford also used this approach to calculate relative reactivities for methanol and formaldehyde (relative to NMHC), based on modeling results for 20 cities.[6] More recently, Ford has calculated relative reactivities for a number of organic gases, including methanol, formaldehyde, ethanol, and acetaldehyde as a function of NMHC/NO_x ratios for low and high dilution cases which is very useful in comparing the reactivity of these compounds.(7)

The relative reactivities (relative to NMHC) calculated by Ford for methanol, formaldehyde, ethanol, and acetaldehyde are presented in Table 4-1. Relative reactivities at a NMHC/NO_x ratio of 8 were used since the ozone maximum occurs nearest this ratio. The relative reactivity approach was selected for this report above the other approaches for the following reasons: 1) it is consistent with past EPA practice, 2) it can be used to assess large changes in organic emissions, unlike the incremental reactivity approach, and 3) it is not subject to the many limitations of the hydroxyl rate constant approach cited previously. It should be noted, however, that the reactivities of pure compounds calculated using the relative reactivity and incremental reactivity approaches agree fairly well.[7]

In a recent paper, Ford has gone a step further and calculated the ozone-forming potential (both relative and incremental reactivities) per carbon of gasoline and alternative-fueled vehicles.[8] Relative reactivities per mile can be derived by multiplying the total carbon emissions per mile by the relative reactivities per carbon. When this is done, it can be concluded that an E85 or E100 vehicle would definitely provide an ozone benefit when compared to a gasoline-fueled vehicle. An E95 vehicle (the non-optimized vehicle tested by CARB) appears to have roughly the same ozone-forming potential as an optimized M85 vehicle. Based on these results, an optimized E85 or E100 vehicle could potentially have the same ozone benefit as an optimized M85 or M100 vehicle.

It should be noted that the magnitude of the ozone impact of an ethanol-fueled vehicle is difficult to quantify at this time. Emissions data for a vehicle designed to run on ethanol are needed, as well as modeling using city-specific conditions. Exhaust emission characteristics in particular are as strong a function of vehicle design as of fuel type.

The ozone impact of an ethanol-fueled vehicle will be dependent upon the atmosphere into which it is introduced. Factors such as the NMHC/NO_x ratio will be important, perhaps even more so than for methanol-fueled vehicles. Ethanol-fueled vehicles emit ethanol and acetaldehyde. The ethanol reacts in the atmosphere to form more acetaldehyde. Similarly, methanol-fueled vehicles emit methanol and formaldehyde, and the methanol reacts in the atmosphere to form more formaldehyde. At low and moderate NMHC/NO_x ratios, both formaldehyde and acetaldehyde exhibit high reactivity due to their high reaction rates with OH radicals and photolysis to form radicals. Formaldehyde photolyzes more rapidly than acetaldehyde. These factors become less important, and the NO_x removal characteristics become more important, as the NMHC/NO_x ratio increases. Acetaldehyde has NO_x sinks in its photooxidation mechanism, because it reacts to form peroxyacetyl nitrate (PAN). These NO_x sinks cause acetaldehyde to have low reactivity at high NMHC/NO_x ratios (i.e., NO_x limiting conditions which acetaldehyde exacerbates). Formaldehyde's reactivity also decreases with increasing NMHC/NO_x ratios, but is not as sensitive to the NMHC/NO_x ratio as acetaldehyde, because formaldehyde does not have significant NO_x sinks in its mechanism.[2] Similarly, when examining the relative reactivities of ethanol and methanol in reference [7], ethanol is more reactive than methanol at the low and moderate NMHC/NO_x ratios (including the ratio at which maximum ozone is formed) which reflects the importance of ethanol's higher reaction rate with the hydroxyl radical under these conditions. At higher NMHC/NO_x ratios, ethanol appears less reactive than methanol due to the increased importance of the minor NO_x sinks in ethanol's photooxidation mechanism.

As mentioned previously, acetaldehyde reacts in the atmosphere to form PAN. A preliminary study of the effects of enhanced acetaldehyde emissions from vehicles using ethanol and ethanol blends on PAN concentrations in urban air has been conducted in Rio de Janeiro, Brazil.[9] The authors conclude that increased acetaldehyde emissions from ethanol-fueled vehicles lead to an apparent increase in the formation rate for PAN, even in the vicinity of large sources of NO and other nitrogen oxides. A more recent study measured ambient levels of acetaldehyde, formaldehyde, and acetone in three major urban areas of Brazil.[10] Acetaldehyde concentrations in urban areas of Brazil are substantially higher than those measured elsewhere. The authors conclude that the most likely cause for high ambient levels of acetaldehyde is the large scale use of ethanol as a vehicle fuel in Brazil.

It is difficult to extrapolate these results to the U.S. because the Brazilian experience is not representative of U.S. conditions. For example, the vehicles in Brazil are not equipped with catalysts, whereas most vehicles in the U.S. have some form of catalyst. When properly operating, catalysts are very effective at decreasing unregulated emissions such as acetaldehyde.[11,12] Other differences that could significantly alter the findings include climate, elevation, population, vehicle age and age distribution of the fleet, maintenance practices, driving habits, and local industrial activity. In addition, a limitation of the studies appears to be the lack of a good pre-ethanol acetaldehyde baseline in Brazil. The studies can be used in a qualitative sense, however, as suggestive of potential PAN and acetaldehyde increases with the use of ethanol fuel.

4.2 Air Toxics

The emissions of air toxics from ethanol fueled vehicles should be similar in composition to those of methanol fueled vehicles. As indicated in Table 4 of Attachment 5 of the Methanol Special Report [5], neat methanol (and thus neat ethanol) vehicles can probably be engineered to have only 10% of the carcinogen emissions as gasoline vehicles, assuming successful commercialization of technology currently being tested in prototype vehicles. For FFV's the benefits would not be as great, but would be roughly similar to those given in Table 4 of the Methanol Special Report.

Relative to methanol, ethanol has the advantage of being less toxic than methanol, and acetaldehyde (the prime aldehyde emitted from ethanol fueled vehicles) is less carcinogenic than formaldehyde (the prime aldehyde from methanol fueled vehicles). As with methanol, the emissions of some substances will be closely related to the substances (such as gasoline, denaturants, and flame visibility additives) which are also present in the fuel. The projections for the year 2005 assume a gasoline composition the same as current. Significantly different gasoline compositions would be considered to be reformulated gasoline, which is another alternative fuel to be covered in a separate report.

4.2.1 Ethanol

Ethanol is not considered a toxic pollutant at levels likely to be inhaled due to its use as a motor fuel. Acute effects of exposure to ingested ethanol are less severe at equal exposure levels than methanol, and it is reasonable that inhaled exposure would behave similarly. Some studies have suggested that ethanol has carcinogenic effects when ingested. [13] It is likely that the carcinogenic effects of inhaled ethanol are negligible, since inhalation exposures at the concentrations that could be reasonably expected would be small; however, according to EPA's most commonly used, linear no-threshhold carcinogenicity model, even very low exposures of any carcinogen are a potential concern.

Other sources of possible exposure to ethanol include fuel production, transportation, and handling. Based on the very limited health data available for ethanol, it can only be stated qualitatively that the health effects from these sources would be less than (or at worst, no greater than) from methanol or gasoline.

4.2.2 Benzene

Benzene is projected to account for about 20% of the carcinogenic emissions of gasoline vehicles in 2005.[14] While it is theoretically possible for benzene to form from ethanol combustion, significant quantities of it are not expected. Test data have indicated some benzene from M100 and E95 vehicles [1], but these vehicles had also been operated on gasoline which would allow hydrocarbons from the charcoal canister to be purged and then form benzene during combustion in the engine. This would not occur with a dedicated E100 vehicle. It is also possible that small amounts of benzene could be generated when lubricating oil burns.

EPA cancer estimates include a minimal amount of exhaust benzene to account for its possible formation. The 97% reduction in benzene for methanol vehicles relative to gasoline which was used in the methanol report will also be assumed for E100 vehicles. FFV's will emit benzene in quantities which are related to the amount of aromatic hydrocarbons in the gasoline and the amount of gasoline used. In the case of E85, a reduction of 85% can be used as an approximation, although arguments can be made for somewhat smaller reductions.

4.2.3 Aldehydes

Directly emitted and indirectly formed formaldehyde is projected to account for about 8% of the carcinogenic emissions from gasoline vehicles in 2005.[14] Ethanol fueled vehicles are expected to emit formaldehyde at a rate roughly equal to or slightly greater than a gasoline vehicle, although much less than that of a similarly engineered methanol vehicle (whether FFV or neat alcohol fueled). [1,15 - '79 SwRI blends report]. However, in the absence of a catalyst system optimized for aldehyde control, acetaldehyde emissions are expected to increase substantially relative to a gasoline vehicle, as is the case with formaldehyde from a methanol fueled vehicle. Acetaldehyde has a much lower carcinogenic potency than formaldehyde, so it is expected that the dominant effect in aldehyde potency from ethanol vehicles would be due to formaldehyde, and this is not likely to be much greater than that from a gasoline vehicle.

Acute non-cancer effects possible from aldehyde exposure include eye, nose, throat, and skin irritation, as well as headaches and nausea. Again, acetaldehyde effects are expected to be less then formaldehyde, and emission control measures used for control of hydrocarbon compounds in ethanol vehicle exhaust would also control aldehyde emissions.

4.2.4 1,3-Butadiene

1,3-butadiene is projected to account for about 30% of the carcinogenic emissions of gasoline vehicles in 2005.[14] Ethanol combustion is not expected to produce any significant 1,3-butadiene. FFV's though will emit 1,3-butadiene in the exhaust hydrocarbon portion.

4.2.5 Other Air Toxics

Polycyclic Organic Matter (POM) emissions are projected to account for about 22% of the carcinogenic emissions of gasoline vehicles in 2005.[14] Although no POM emission data from E100 vehicles exist, the combustion of very low molecular weight ethanol (or methanol in the case of M100 vehicles) would not be expected to form any substantial quantity of the much higher molecular weight polycyclic organic compounds. To account for possible formation of small quantities, such as from the oil, the 99% reduction in POM for methanol vehicles used in the methanol report has been assumed for E100 vehicles. In the case of E85, a reduction of 85% can be used, since POM would still be formed from the hydrocarbon portion of the fuel (although as with benzene, a smaller reduction is possible).

Gasoline refueling vapors are projected to account for about 17% of the carcinogenic emissions of gasoline vehicles in 2005.[14] No gasoline refueling vapors would be emitted with use of 100% ethanol. In fact, the low vapor pressure of 100% ethanol would result in very little ethanol emissions as well. Gasoline refueling vapors would be emitted with FFV's to the degree that gasoline is used in the fuel, adjusted for the much greater volatility of gasoline than ethanol; i.e., gasoline would comprise a greater percentage of the vapor than the liquid.

Peroxyacetyl nitrate (PAN) is another pollutant associated with ethanol fuel use, as mentioned in the previous section on ozone. Besides its role in ozone formation, PAN is somewhat of an acute toxic compound in its own right. Given high enough concentrations, it is capable of producing eye irritation, blurred vision, and eye fatigue. However, the concentrations at which effects have been found are much higher than are likely to occur in the atmosphere, and ozone concentration would be a problem well before PAN would reach irritant levels.[16]

4.3 Global Warming

Carbon Dioxide (CO_2) is one of the "greenhouse gases" which means that it increases the tendency of the atmosphere to absorb heat radiated from the earth and thus increases the average temperature of the atmosphere. Carbon dioxide is also the end product of complete combustion of the carbon contained in hydrocarbon fuels. In fact, the goal of decreased exhaust emissions and increased fuel economy implies improvement of combustion efficiency to maximize the conversion of fuel carbon into CO_2, thus minimizing the formation of incomplete combustion products (such as carbon monoxide, benzene, 1,3-butadiene, POM, and other pollutants). Therefore, use of any carbon containing fuel causes CO_2 addition to the atmosphere, and the issue is how much of that carbon can then be removed from the atmosphere and be reconverted into feedstock for future fuel. With fossil fuels such as petroleum products, the rate of CO_2 addition to the atmosphere is much greater than the rate the earth can reabsorb it and convert it into petroleum, limestone, etc. since that takes thousands of years. However, with ethanol, to the degree that it is derived from vegetation (i.e., trees or agricultural products) the reabsorption of the carbon can be as fast as it is emitted, resulting in no net increase in CO_2 in the atmosphere.

4.3.1 Impact of Ethanol from Corn

In the production of ethanol from corn, as is currently done, there is still a fair amount of fossil fuel used.[17] For instance, about 7.4 million BTU of petroleum and natural gas products are used for fertilizer, tractor and truck fuel, and grain drying for one acre of corn. Also, coal is usually used to provide process heat in the ethanol plant, and if the ethanol plant does not cogenerate electricity, its consumption of electricity increases the use of natural gas, coal, or oil at an electric power plant (assuming it is not nuclear or hydroelectric). The following discussion provides a brief analysis of this net release of CO_2 from the use of corn derived ethanol in vehicles as compared to that of gasoline.

As mentioned earlier in the economic analysis section under distribution to consumers, an optimally designed vehicle fueled with 100% ethanol could be expected to have about 87% of the mile per gallon fuel economy compared to a gasoline-fueled vehicle. A vehicle fueled with 85% ethanol could be expected to have a mile per gallon fuel economy about 72% that of a gasoline fueled vehicle. This means that one needs about 15-39% more ethanol on a volume basis than gasoline. A mile per gallon figure of 27.5 miles per gallon is used for illustration since that is the Federal fuel economy standard for new cars in that time frame.

Use of this figure results in the following amounts of fuel being consumed for each mile of vehicle travel.

Type of Fuel	Fuel Consumption (gallons per mile)
Gasoline	0.0364
100% ethanol	0.0418
85% ethanol	0.0505

There is controversy on the inputs used to calculate the amount of energy needed and CO_2 released in production and combustion of gasoline and ethanol.[18,19] A point of particular debate is the energy needed in ethanol production, which can vary by almost a factor of two depending on the process used and especially on whether waste heat is recovered for purposes such as cogeneration of electricity. A recent draft EPA report examined the effects of fuel ethanol production and use on carbon dioxide production and emissions.[20] This report used as input a number of non-EPA reports.[21-23]

Table 4-2 lists the draft EPA estimates of the amount of CO_2 from production and use of a gallon of gasoline and ethanol. The biggest variable in these numbers is the CO_2 emitted (from energy consumed) during ethanol production. The typical range of energy needed for ethanol production is given in various studies as 40,000-60,000 BTU per gallon of ethanol, not including the energy needed for byproduct drying. There are competing estimates, but since expanded ethanol production would be expected to use the best available plant technology, the lower number (40,000 BTU per gallon) should serve as a reasonable average. Combining this number with energy efficiencies and other factors discussed in reference [20] gives the 7.97 lb CO_2 per gallon shown in Table 4-2.

These figures and the gallons per mile numbers can be combined to give the CO_2 emission estimates shown in Table 4-3 for the current gasoline vehicle scenario and an expanded ethanol vehicle scenario. These numbers show lower total CO_2 emissions in the ethanol vehicle case than in the gasoline case. The impacts of land use changes on CO_2 were not explored but are potentially important in a large program. For example, growing corn or other crops in areas that were forested could affect the overall CO_2 balance.

Table 4-2

Carbon Dioxide Emissions from Fuel Production and Use

Source	Pounds of CO_2 Per Gallon of Fuel	
	Ethanol[a]	Gasoline
Gasoline production		3.23
Gasoline combustion		19.27
Ethanol combustion	[12.6][b]	
Corn farming	4.58[c]	
Ethanol production	7.97[d]	
By-product drying	4.19	
Credit for displaced soybean production[e]	(1.37-1.47)	
TOTAL	15.27-15.37	22.50

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[a] These are per actual gallon rather than gasoline-equivalent gallon. On a gasoline-equivalent basis the ethanol numbers would be 15%-50% greater than shown, depending on efficiency of the vehicle in which the ethanol is used.

[b] CO_2 released from fermentation and ethanol combustion comes from CO_2 captured through photosynthesis in growing the corn crop and therefore is not counted in the total; also the CO_2 released during fermentation is assumed to be recovered and to displace CO_2 that would have been generated from incremental fossil fuel. This CO_2 is not counted in the total. This number comes from Reference [18].

[c] Includes tractor and equipment fuel, fertilizer, grain drying, and other energy uses such as pesticides.

[d] Low end of current typical range is shown, corresponding to large new energy efficient plants fueled with coal.

[e] Increased ethanol production from corn and increased byproducts would decrease the soybean market. The credit comes from the decrease in fossil fuel use for soybean farming. See Reference 20 for details.

Table 4-3

Net Carbon Dioxide Emissions per Mile of Vehicle Travel[a]

Type of Fuel	CO_2 Emissions (grams per mile)	Reduction Relative to Gasoline
Gasoline	371	0
100% ethanol	290-291	-21 to -22%
85% ethanol	350-352	-5% to -6%

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[a] This is total CO_2 emissions per gallon from both fuel production and combustion (minus the CO_2 reabsorbed into ethanol feedstock but no credit for commercial use of fermentation CO_2), divided by a gasoline-equivalent fuel economy of 27.5 miles per gallon. New large energy efficient ethanol plants are assumed, since this analysis is for a greatly expanded ethanol program.

4.3.2 Impact of Ethanol from Cellulosic Biomass

The energy balance for production of ethanol from cellulosic materials is much better than for production from corn, since the energy inputs needed for producing the feedstock are much less. Also, an otherwise worthless portion of the feedstock can be used for process energy, rather than using coal. Potentially, all the energy needs for cellulosic biomass production and conversion could come from the cellulosic material itself, although in the early stages of commercialization this might not be the case. Even so, the ratio of fossil carbon burned to carbon available for end use has been estimated to be very low (e.g., 0.0-0.21).[24]

Regarding greenhouse effects, this means that the growing of cellulosic feedstocks (trees and herbaceous crops) could reabsorb a quantity of carbon dioxide virtually equal to the amount emitted in the production/use of ethanol produced from these sources.

4.4 Agricultural Side Effects on the Environment

With increases in ethanol production, the agricultural side effects on the environment must also be considered. Some of the issues to consider include the effect of the increased agriculture on surface and ground water (e.g., from changes in water run-off patterns, from increased amounts of fertilizer and pesticide run-off), soil erosion, and wild life. Also, the effect of increased agriculture on forests (including rain forests if increased crops are grown in the Tropics) has to be evaluated.

A comprehensive treatment of issues such as these is not possible at this time. Much depends on the scale of ethanol production, what gets displaced for increased farm land, the crops used, and the various technologies used in farming. One can envision a long term scenario in which biomass crops are grown in a manner that is gentler on the environment than current food crop cultivation. On the other hand, placing any presently uncultivated and unharvested land into active biomass production will inevitably have some effect on its ecology.

4.5 Other Environmental and Health/Safety Issues

4.5.1 Spill Issues

Use of ethanol as a motor vehicle fuel would necessarily involve more transport of neat or near-neat ethanol, and consequently more opportunities for accidental spills of a significant quantity. The modes of shipment would certainly include barge, rail tank car, and tank truck. Transport by multi-product pipeline, dedicated pipeline, and ocean-going tanker are also possible, depending on the scale and location of use and the source of supply. As with transport of gasoline via these modes, accidental releases are inevitable over a long enough period of use. Barge and tanker shipment pose a risk of a spill into the open ocean, coastal waters, rivers, or the Great Lakes. The other modes would more typically result in spills onto land first, with possible run-off into surface waters.

If ethanol were involved in a spill into the ocean, into a lake or river, onto land, or into drinking water supplies, the question arises as to whether a greater environmental and public health hazard would be posed relative to a petroleum fuel spill. The risk relative to other clean fuels, particularly methanol, is also of interest. An ethanol fuel spill into aquatic systems or on land indeed poses environmental and health concerns because of the fuel's toxic effects in high concentrations, and it could be expected that there would be a slightly larger number of spills (about 20% "per vehicle") for a given mode of transport, because of the larger quantities of ethanol fuel that would have to be transported. The modal pattern of ethanol transport could be quite different than that of either petroleum or methanol fuel, with less reliance on ocean shipment.

As a result of ethanol's inherent properties of water solubility, biodegradability, and relative ease of complete evaporation, it could quickly dilute to non-toxic concentrations, disperse downstream, decompose if spilled into large bodies of water, and evaporate or decompose if spilled on land areas. Thus, in many scenarios, an ethanol spill should not be as hazardous as a petroleum spill.

In comparison to petroleum fuels, a tanker spill of ethanol into the ocean should pose less risk to aquatic life. Ethanol's water solubility allows for rapid dispersion and dilution and, therefore, short exposure durations. Also, ethanol's quicker biodegradation than that of crude oil, diesel fuel, or gasoline results in shorter residence times of the fuel and faster recolonization of life at spill sites, with less severe long-term effects of spills on animal life and on the environment. In general, cleanup of ethanol spills requires less extensive efforts and costs than cleanups associated with spills of water-insoluble petroleum fuels. Small ethanol spills usually do not require any cleanup efforts because of the effectiveness of natural biodegradation, while large ethanol spills may require aeration of the water (to supply depleted oxygen to marine life and speed biodegradation) and/or use of ethanol-destroying bacteria.

Ethanol spills into rivers and other moving bodies of water also benefit from the fuel's water solubility and biodegradation. Again, in contrast to petroleum fuels, ethanol spilled into a river from, for example, a barge, is quickly diluted and carried downstream. Cleanup of an ethanol fuel spill into a moving body of water would be handled similarly to that of a spill into the ocean.

Although, like petroleum fuels, ethanol in high concentrations is toxic to plant and animal life, its toxic effects after a spill onto land are of shorter duration and are less acute than those exhibited by a petroleum fuel spill. Again, ethanol's inherent properties of relative ease of complete evaporation and biodegradability play a positive role. Its more rapid evaporation from the earth allows for less to be absorbed into the soil and water table. (It is important to note that while some of the lighter ends of gasoline evaporate very quickly, its heavy components require long periods of time before evaporation occurs.) However, if absorbed, ethanol's larger degree of biodegradability facilitates decomposition by micro-organisms present in the soil. Because of its shorter retention periods near a spill site, cleanup of an ethanol spill on the earth requires less effort than that of a petroleum fuel spill. In the event of a massive spill, however, enhancement of the natural biodegradation process of ethanol may be beneficial.

Since ethanol's solubility in water and, hence, rapid dilution and dispersion are considered advantages in spills into large and/or quickly moving water masses, most scenarios where drinking water is at risk would be less severe with ethanol than with petroleum. In some situations, however, such as a river spill located very near a drinking water supply intake ethanol may indeed contaminate a water supply that would have escaped contamination by petroleum fuel. However, ethanol has a taste and odor that most adults can recognize and avoid. With the possible exception of fetuses and pregnant women, consumption of drinking water with low levels of ethanol should not be acutely toxic.

Fuel ethanol will contain denaturant, and may be shipped or stored mixed with gasoline. Consideration needs to be given during the choice of a denaturant as to whether it remains detectable at any concentration that could be toxic. Gasoline mixed with ethanol will tend to separate out when the mixture reaches water. It is known that there is some greater tendency for aromatic hydrocarbons to mix into the water when methanol is also present. This may also occur but perhaps to a lesser degree with ethanol. Studies on the disposition of ethanol spills very near drinking water supplies are not available, and further study by EPA and other organizations would be useful.

Most of the above discussion applies equally to ethanol and methanol. Methanol would evaporate from an on-land spill faster than ethanol. The relative toxicity of methanol and ethanol to fish and other organisms at a given dilution is largely untested. One alcohol may produce a somewhat larger "kill zone" before non-toxic dilution occurs. The most significant difference between the two alcohols is likely to be that humans can relatively safely consume ethanol if it finds its way into a water supply.

4.5.2 Leak Issues

The previous section addressed the potential consequences of sudden releases of significant quantities of ethanol fuel. Slower leaks and continuous releases of small quantities are also of interest.

Because of the biodegradability of ethanol, smaller routine releases in circumstances that allow for good dilution should not present an environmental problem. For example, transfer losses between ship and shore or flushing of cargo tanks would at most encourage a higher local concentration of ethanol-digesting bacteria.

Leaks into underground water are a potentially greater concern with all fuels because of the more restricted dilution conditions that can exist. Also, while bacteria are present in soil and underground water supplies, they are sparser than in the ocean and surface waters. Ethanol fuel would be most often stored in underground tanks, creating the opportunity for both relatively sudden loss of contents and for undetected leakage over a period of time.

The first point to note with regard to leaks from underground tanks is that industry practices in underground fuel storage are changing drastically in response to recent legislation. Double wall tanks, leak monitors, and periodic leak testing will become standard practice for gasoline tanks. These techniques can be extended by regulation to other fuels as judged necessary.

If a leak does occur, there will be several differences between the consequences with ethanol compared to that with petroleum fuels. Ethanol and petroleum fuels have different hydrological effects in soils and may migrate downward at different rates, providing more or less time for evaporation instead. Once in contact with the water table, ethanol will tend to mix and dilute more quickly than a petroleum fuel and to biodegrade more quickly. (There may be a zone in which the ethanol concentration is too high for biodegradation to occur.) If ethanol reaches a drinking water well, there is little health risk. Ethanol is not toxic and is detectable by both odor and taste.

Methanol and ethanol would behave very similarly to each other in an underground spill, particularly in comparison to their sharp differences from petroleum fuels. Methanol, however, is toxic at concentrations that are of no concern for ethanol and is not detectable by taste or odor. Dyes or odorants may be needed for methanol that can be omitted with ethanol.

4.5.3 Fire Issues

Ethanol, like all combustible fuels such as gasoline, poses a potential human safety risk. Because of the differences in the physical and chemical properties of ethanol and gasoline, the human safety risks of neat ethanol are dramatically different than those of gasoline. Based on what is currently known, ethanol would appear to offer fire safety benefits compared to gasoline. Further research is necessary to identify those areas where precautions are needed.

With regard to fire safety of ethanol, there are two main advantages and two main disadvantages. The advantages, along with the possibility for mitigating the disadvantage, cause the fire safety risks of ethanol to be lower than for gasoline. Ethanol's low volatility, relatively high lower flammability limit*, and low vapor density cause it to be much less likely to ignite in an open area following a spill of fuel or release of vapor. In addition, once it does ignite, ethanol's low heat of combustion and high heat of vaporization cause it to burn much more slowly, releasing heat at roughly one-fifth the rate of gasoline. However, these same combustion properties cause ethanol to be in the flammable range inside fuel storage tanks under normal ambient temperatures (45-108° F), while gasoline is virtually always too rich to ignite. Fortunately, precautions can be taken to prevent flammable vapor/air mixtures from forming in storage tanks (e.g., nitrogen blanketing, bladder tanks, floating roof tanks) or to prevent ignition sources from entering the tanks (e.g., flame arresters, removing or modifying in-tank electrical devices) thereby mitigating any additional risk.

---

* Ethanol will not ignite in air at concentrations below about 3.3 percent while gasoline will ignite at concentrations as low as 1.4 percent.

Also, while ethanol tends to burn with a much more visible flame than methanol, flame visibility and radiation are less than that of gasoline.

4.5.4 Ingestion

Two ingestion scenarios are of interest. First, neat or near-neat ethanol fuel could be accidentally ingested, as gasoline is sometimes now. Second, ethanol fuel could be diluted for beverage purposes to avoid alcoholic beverage taxes or age restrictions on purchasing alcoholic beverages.

Most gasoline ingestion episodes are due to adults attempting to siphon gasoline from a vehicle, or children drinking from small containers of gasoline intended for use in small household engines or for degreasing. Ethanol-fueled vehicles can be equipped with devices to prevent siphoning. Ethanol fuel storage in homes should be rare, since household engines will not run on ethanol and ethanol would not be a good degreaser. Thus the incidence of ethanol fuel ingestion should be far less than for gasoline.

If it were to occur, ingestion of several ounces of pure ethanol would not be harmful to most adults, but it would be of concern for a child. In large enough quantities, even adults can experience serious effects including death, but the quantities involved are associated with alcohol abuse or suicide attempts and are thus greater than would be expected from accidental ingestion.[25] In addition, ethanol fuel will contain a denaturant to segregate it from taxed beverage ethanol. The denaturant may be toxic. Presently, chemical and fuel ethanol may legally be denatured with methanol. Methanol is toxic, but has no taste or odor to discourage ingestion. It will be important for the denaturant in fuel ethanol to have an unpleasant taste and smell.

Despite the presence of the denaturant, fuel ethanol may be deliberately or mistakenly added to beverages. Incidences with methanol were common in the past in the U.S. and are still reported in other countries. Bootleg beverages made with ethanol fuel could be of health concern due to the presence of denaturants in the original fuel. Unsophisticated users may not understand the risk posed by the denaturant or may mistakenly believe they have removed or neutralized it. If ethanol fuel is to be widely used, research to identify the best denaturant should be undertaken. Again, unpleasantness would be a better working principle than toxicity.

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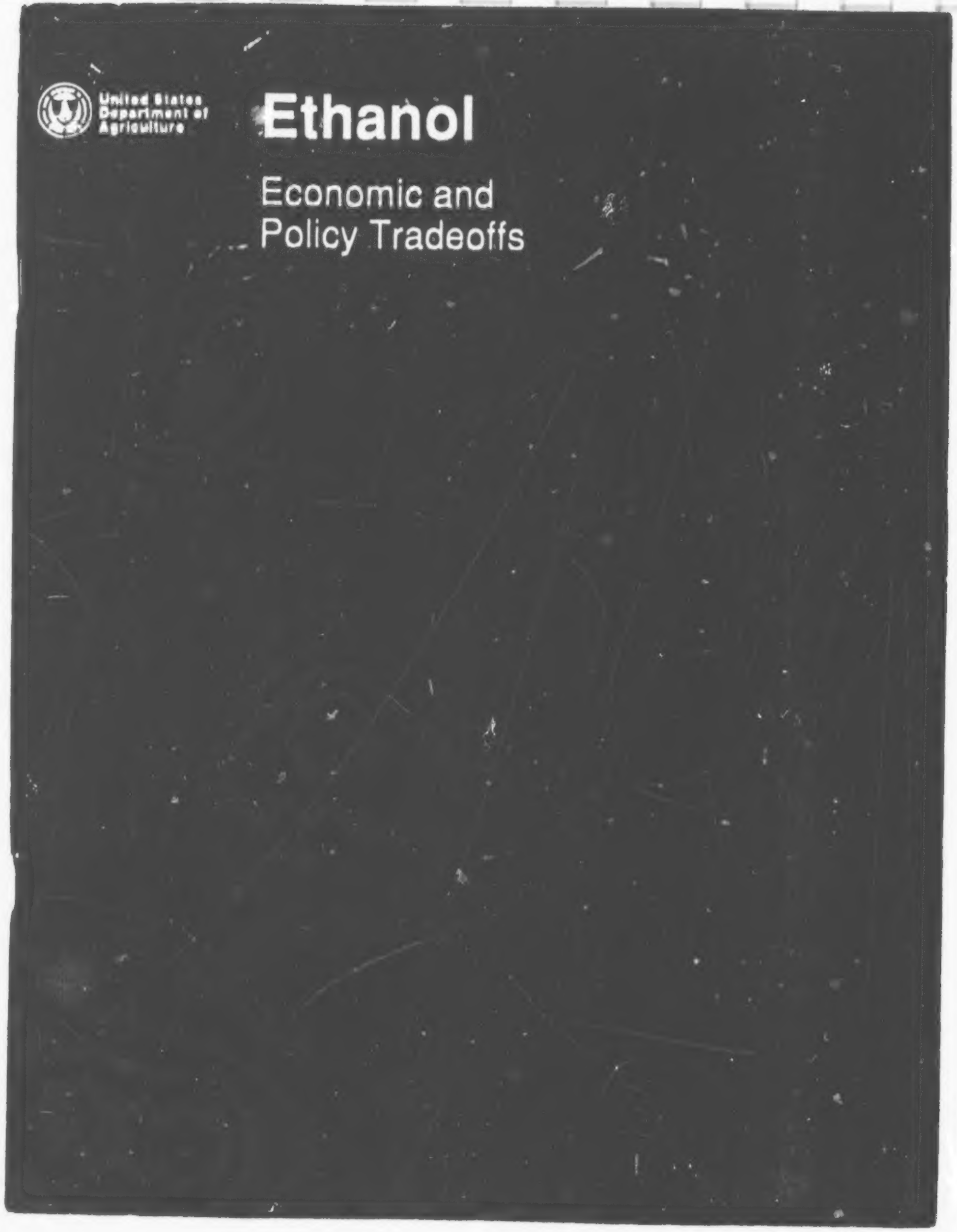
APPENDIX A

Summaries of Previous U.S. Government Ethanol Studies



United States
Department of
Agriculture

Ethanol

Economic and Policy Tradeoffs

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EXECUTIVE SUMMARY

With the existing Federal fuel excise tax exemption, ethanol will likely remain cost competitive as a fuel blending agent, especially given ethanol's value as an octane enhancer. Without the exemption and given the agricultural and energy market conditions likely to prevail over the next 10 to 15 years, it may be difficult for ethanol to compete on a direct cost basis with many other fuel blending agents. While low corn and grain prices are favorable for ethanol, the glut in world petroleum markets works against ethanol's competitiveness. The nonmarket benefits of ethanol in meeting environmental, energy security, and agricultural goals are positive but limited, with alternatives for meeting these goals available.

The study develops an information base on current and future conditions in the industry. Current and future ethanol production technologies are assessed. Breakeven conditions for ethanol are established recognizing the sensitivity of ethanol's competitiveness to new production technologies and prices for corn, byproducts, crude oil, and alternative fuel blending agents. From this basis, the contribution of ethanol production and use to Federal policy objectives is addressed. The market price of ethanol may not fully reflect the value of ethanol in achieving various policy goals. Effects of ethanol production and use not captured by the market price may provide a justification for Federal involvement.

Ethanol production costs vary considerably among producers and over time. Since 1980, net corn costs have ranged from 70 cents per gallon of ethanol to as little as 6 cents during the first quarter of 1987, averaging 56 cents per gallon. Operating costs for large plants currently average 47 cents per gallon with a range of 40 to 59 cents. Capital costs of 19 cents per gallon of ethanol produced are achieved when fermentation and distillation capacity is added to an existing wet mill with excess corn grind capacity. Most future expansion would utilize abandoned industrial capacity at capital costs per gallon of 33 to 38 cents compared with as much as 48 cents for a fully new site.

A state-of-the-art plant built today would achieve a 9-cent cost advantage over the average of existing plants. Additional advances likely in the next 3 to 5 years could reduce costs by another 5 cents. In the longer term, technologies that convert feedstock material other than sugars and starches offer an opportunity to reduce feedstock costs. These technologies are likely to be more costly than current technologies given currently low corn costs but would become cost competitive if corn prices rise relative to other biomass feedstocks. Any decrease in crop production costs resulting from traditional crop breeding, applications of biotechnology, or from broader sets of reductions in input costs would reduce the cost of ethanol feedstocks.

Ethanol is cost competitive as a fuel blending agent with the Federal excise tax exemption, corn costs of $2.00 per bushel, and byproduct recovery of 50 percent of the cost of corn if crude oil prices are $20 dollars per barrel or more. Extension of the excise tax exemption to the year 2000 would provide the incentive to expand industry production by as much as 1 to 2 billion gallons by 1995, up from the current 800 million gallons. Without the Federal subsidy and with $2.00 per bushel corn, crude oil prices must be at least $40 per barrel for ethanol to be cost competitive.

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Ethanol's competitiveness also depends on how it is used in fuel. A gallon of ethanol contains two-thirds the energy value of a gallon of gasoline but has an octane value over 30 percent greater than regular unleaded gasoline. Ethanol producers have begun marketing ethanol for its higher value as an octane enhancer. Currently, ethanol prices do not generally reflect the octane value of ethanol. Rather, ethanol is frequently priced, net of the Federal and applicable State subsidies, below wholesale gasoline prices to overcome costs of blending ethanol and resistance to blend fuels.

Domestically supplied energy has presumed benefits in enhancing energy security although even energy independence does not isolate the domestic economy from energy market shocks to the economies of our trading partners. Energy prices and their impacts are tightly linked through world trade markets. Current annual ethanol production accounts for approximately 1/200 of the energy content of gasoline and less than 1/1,000 of all energy used in the United States each year.

Ethanol production is self-limiting in terms of its contribution to national energy supplies. Production levels of two or three times current levels, while still a small proportion of total energy use, would begin to place strong upward pressure on corn and other grain prices, thereby increasing the production cost of ethanol and reducing its competitiveness compared with alternative energy sources. The broader range of ethanol feedstocks envisioned for the future offers greater production potential but they are constrained and relatively costly in terms of delivered energy content compared with other long-term liquid fuels based on abundant domestic resources such as coal and shale oil.

Ethanol use can help meet certain requirements of the Clean Air Act. Ethanol, blended at 10 percent with gasoline, has a demonstrated result of reducing vehicle carbon monoxide (CO) emissions. Other oxygenates including methanol and MTBE, an octane enhancing additive made from methanol and petroleum refinery products, also reduce CO emissions.

Use of ethanol blend fuels tends to increase ozone concentrations which are also limited by the Clean Air Act. Ethanol increases the volatility of the base gasoline with which it is blended, potentially increasing lower level atmospheric ozone concentrations. Carbon monoxide, however, is a winter problem whereas ozone is a summer problem, allowing seasonal blending of alcohols to contribute to reductions in CO emissions without increasing ozone problems. MTBE does not substantially increase fuel volatility.

Farm income would increase modestly if the ethanol industry expanded. The market price for corn would increase but the gain to total income would be small in the near term, government payments to corn producers would fall as the gap between the market and target prices of corn narrow. By 1995, when market prices push above target prices, gains to corn producers would be greater. Income to oilseed producers (such as soybean, cotton seed, and sunflower seed producers) would fall as a result of the expanded supply of corn oil and protein meal feeds that are byproducts of ethanol production. Other agricultural producers would experience minor effects. Producers of grains other than corn would benefit as prices of all grains followed corn prices. Livestock producers would gain from lower protein meal prices but lose as a result of higher grain prices, the net effect dependent on the specific price effects and the importance of grain versus protein feeds in the ration. The total increase in farm income from a 1.9-billion-gallon addition to the current 800-million-gallon ethanol industry would be less than $1 billion in 1995 and lower in earlier years.

To achieve significant increases in ethanol production and the estimated savings in agricultural program outlays, it would be necessary to extend the Federal excise tax exemption on ethanol blend fuels through the year 2000. The agricultural program savings would exceed the reductions in Highway Trust Fund revenues through 1995. Beyond 1995, however, Highway Trust Fund revenue losses exceed farm program savings under the assumption of recovery in the agricultural sector and continuance of current agricultural programs without significant change. By 1999, the added budget costs would exceed budget savings realized prior to 1995.

Fuel Ethanol Cost-Effectiveness Study

Final Report

National Advisory Panel on Cost-Effectiveness
of Fuel Ethanol Production

November 1987

FOREWARD

There is renewed interest in expanded fuel ethanol production as it would relate to improving the environment, national security, domestic economy, foreign trade, government expenditures, and farm income. There is particular interest in the cost-effectiveness of ethanol production with modern plants, utilizing the best available technology.

Based on an act of Congress, Secretary of Agriculture Richard E. Lyng named a seven-member panel representing a cross section of interests in fuel ethanol to make an assessment of a broad range of questions. The Panel presents this report as a current appraisal of the cost-effectiveness of fuel ethanol to U.S. society, U.S. government policy, and to the economy.

The report is drawn from data and information provided by fuel ethanol producers, the Congressional Research Service, the Environmental Protection Agency, Department of Agriculture, Department of Energy, and others interested and willing to share with the Panel the facts and information available.

This study should be helpful to those interested in becoming producers or marketers of fuel ethanol as well as to Congress and state legislatures who will play a critical role in any expansion of this multifaceted industry.

The Panel expresses its appreciation to the Panel support staff and all who contributed to the report.

Dr. C. Wm. Swank
Chairman

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PANEL MEMBERS

Members of the Panel were appointed by the Secretary of Agriculture in accordance with the Farm Disaster Assistance Act of 1987 (P.L. 100-45). The Chairman was selected by the Secretary from among the members.

Chairman

Dr. C. William Swank
Executive Vice President
Ohio Farm Bureau Federation, Inc.

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TABLE OF CONTENTS

Fuel Ethanol Cost-Effectiveness Study

Page

Panel Mandate xi

Preface xiii

Summary and Conclusions xv

1. Fuel Ethanol Industry Overview 1-1
   - 1.1 History of Fuel Ethanol 1-1
   - 1.2 Current Status 1-1
   - 1.3 Foreign Ethanol Industry 1-5
   - 1.4 Fuel Ethanol's Role Today 1-5
   - 1.5 Government Support of Fuel Ethanol 1-6
   - 1.6 Findings 1-11

2. Fuel Ethanol Technology and Economics 2-1
   - 2.1 Introduction 2-1
   - 2.2 Fuel Ethanol Feedstocks 2-1
   - 2.3 Fuel Ethanol Processes 2-3
   - 2.4 Ethanol Production Cost Factors 2-8
   - 2.5 Fuel Ethanol Marketing 2-12
   - 2.6 Gasoline Blending Economics 2-16
   - 2.7 Findings 2-20

3. Ethanol Fuels and Agriculture 3-1
   - 3.1 Introduction 3-1
   - 3.2 Current Outlook for U.S. Agriculture 3-4
   - 3.3 Impact of Ethanol Production on the Corn Subsector 3-5
   - 3.4 Impacts of Ethanol Production on Other Feed Grains 3-15
   - 3.5 Impacts of Ethanol Production on Soybeans 3-16
   - 3.6 Impacts of Ethanol Production on the Rural Economy 3-20
   - 3.7 Summary and Findings 3-26

TABLE OF CONTENTS (Cont'd)

Page

4. Air Quality Benefits of Ethanol-Blended Fuel 4-1
   - 4.1 Introduction 4-1
   - 4.2 Carbon Monoxide 4-1
   - 4.3 Ozone 4-7
   - 4.4 The Impacts of Ethanol Blends on Gasoline-Powered Engines 4-13
   - 4.5 Other Environmental Issues 4-15
   - 4.6 Findings 4-18

5. Ethanol and U.S. Energy Security 5-1
   - 5.1 Introduction 5-1
   - 5.2 Costs of Energy Dependence 5-3
   - 5.3 Federal Support to Domestic Energy Industries 5-4
   - 5.4 The Role of Ethanol in National Energy Security 5-5
   - 5.5 Summary 5-8
   - 5.6 Findings 5-10

Bibliography 6-1

Appendix A: Description of Government Corn and Soybean Programs Affected by Ethanol A-1

Appendix B: The Current Outlook for U.S. Agriculture B-1

Appendix C: Vehicle Driveability and Materials Compatibility . C-1

Appendix D: The Ozone Cycle D-1

Panel Support Staff E-1

LIST OF FIGURES

Figure		Page
1-1	U.S. Fuel Ethanol Production, 1979-1987	1-3
1-2	Grain Utilization for U.S. Fuel Ethanol Production, 1979-1987	1-4
2-1	Usage of Feedstocks in Fuel Ethanol Production Facilities	2-2
2-2	Dry Mill Processing	2-4
2-3	Wet Mill Processing	2-5
2-4	Fuel Ethanol Marketing	2-15
2-5	Price of 10% Ethanol Blends vs. Base Gasolines	2-17
2-6	Cost of Adding Octane to Gasolines	2-19
3-1	Ethanol Production Scenarios	3-2
4-1	National Trend in Emissions of Carbon Monoxide, 1976-1985	4-3
4-2	Boxplot Comparisons of Trends in Second-Highest Nonoverlapping 8-hour Average Carbon Monoxide Concentrations at 163 Sites, 1979-1985	4-3
4-3	National Trend in Emission of Volatile Organic Compounds, 1976-1985	4-8
4-4	Boxplot Comparisons of Trends in Annual Second-Highest Daily Maximum 1-Hour Ozone Concentrations at 523 Sites, 1981-1985	4-8
4-5	Non-Tampered Evaporative Emissions vs. RVP	4-11
4-6	National Trend in Emissions of Nitrogen Dioxides, 1976-1985	4-17
5-1	Historical and Projected U.S. Oil Imports, 1973-2000	5-2
5-2	Total Discovered Oil (Billions of Barrels)	5-3
5-3	1987 Oil Import Displacement at Various Ethanol Production Levels	5-9

LIST OF TABLES

Table		Page
1-1	U.S. Fuel Ethanol Facilities Currently Operating	1-2
1-2	State Ethanol Fuel Legislation	1-9
2-1	Ranges in Production Cost Factors for Fuel Ethanol	2-13
2-2	Prices of Ethanol Blends vs. Other Gasolines	2-16
3-1	Ethanol Production Scenarios in Relation to Selected Agricultural Commodities	3-3
3-2	Budget Outlays for Price Support Programs: Current Policy	3-5
3-3	Outlook for Corn Production, Use, Stocks, and Prices: Current Policy	3-6
3-4	Scenario 1: Effects on Corn Subsector of Ethanol Production at 1.7 Billion Gallons By 1992-93	3-7
3-5	Net Change in Corn Cash Receipts, Scenario 1	3-10
3-6	Scenario 2: Effects on Corn Subsector of Ethanol Production at 3.4 Billion Gallons By 1992-93	3-11
3-7	Net Change in Corn Cash Receipts, Scenario 2	3-12
3-8	Scenario 3: Effects on Corn Subsector of Ethanol Production Terminated in 1987-88	3-13
3-9	Net Change in Corn Cash Receipts, Scenario 3	3-15
3-10	Corn Milling By-Products	3-17
3-11	Scenario 1: Changes in Corn By-Product Production	3-18
3-12	Scenario 2: Changes in Corn By-Product Production	3-19
3-13	Scenario 3: Changes in Corn By-Product Production	3-20
3-14	Value Added and Employment in the Food and Fiber Sector, 1984	3-22
3-15	Selected Economic Impacts of Changes in Corn Use for Ethanol	3-23

LIST OF TABLES (Cont'd)

Table | Page
4-1 Technology-Specific Per Vehicle Exhaust Emission Effects of Ethanol Blends as a Percent Change from Gasoline.......... 4-5
4-2 Estimated Fleetwide Impact of Ethanol Blends on Carbon Monoxide.......... 4-6
4-3 Nationwide Attainment Projections for Ozone and Carbon Monoxide.......... 4-9
4-4 Estimated Fleetwide Impact of Ethanol Blends on Ozone.......... 4-12
4-5 Average Aldehyde Emissions (mg/mile) of Gasoline and 10% Ethanol/90% Gasoline Blends.......... 4-16
5-1 Summary of Oil Incentives by Type up to 1976 (In Millions of 1986 Dollars).......... 5-6
5-2 An Estimate of the Cost of Incentives Used to Stimulate Energy Production up to 1976 (In Billions of 1986 Dollars).......... 5-7
B-1 Area and Production Changes, 1986-87 to 1987-88.......... B-1
B-2 U.S. Agricultural Commodity Exports: Current Policy.......... B-2
B-3 Program Crop Area: Current Policy.......... B-3
B-4 U.S. Crop Production: Current Policy.......... B-3
B-5 U.S. Carry-Over Stocks: Current Policy.......... B-4
B-6 Net Cash Income: Current Policy.......... B-5
B-7 Budget Outlays for Price Support Programs: Current Policy.......... B-5
B-8 Baseline: Corn.......... B-9
B-9 Scenario 1: Corn.......... B-10
B-10 Scenario 2: Corn.......... B-11
B-11 Scenario 3: Corn.......... B-12

LIST OF TABLES (Cont'd)

Table | Page
B-12 Corn Meal and Oil Production.......... B-13
C-1 Effects of Ethanol-Blended Fuels on Metal.......... C-2
C-2 Overall Driveability Summary.......... C-3
C-3 Summary of Automobile Manufacturer Positions on Alcohol Fuels, 1987 Model Year Vehicles.......... C-5

PANEL MANDATE

Section 13 of the Farm Disaster Assistance Act of 1987 (P.L. 100-45) directed the Secretary of Agriculture to establish a seven-member panel to conduct a study of the cost-effectiveness of ethanol production.

The Act specified that the panel: (1) review and assess the economics and cost of production factors involved in the manufacture of ethanol in modern ethanol production facilities; (2) assess ethanol technology, production, and marketing advances that have enabled the ethanol industry to grow rapidly since the inception of the industry in 1980; (3) assess the economic effect on United States agriculture from fuel ethanol production from United States agricultural commodities; (4) review and analyze the tradeoffs between federal production and marketing incentives for fuel ethanol and other agricultural programs designed to enhance farm income and adjust agricultural production; (5) analyze the effect on the agricultural economy resulting from increasing levels of ethanol production; (6) analyze the affect fuel ethanol production has on agricultural prices and farm income; and (7) analyze the effect of increased ethanol production on the balance of trade, energy security, and air quality in the United States.

The original legislation, enacted May 27, 1987, specified that the panel submit a report to Congress describing the results of this study no later than 90 days after the date of the Act's enactment. In response to a request by the panel for a time extension of 90 days, the Senate and House of Representatives passed S. 1597 on August 7, 1987 to amend the Farm Disaster Assistance Act to extend the reporting date to 180 days after the date of enactment of P.L. 100-45.

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by 1992-93. Scenario 2 supposes a quadrupling to 3.4 billion gallons/year by 1992. These two scenarios represent moderate and high-growth scenarios if ethanol production is encouraged or its economics improve in the near future. Scenario 3 examines the impacts of a sudden termination of ethanol production in 1987-88, and its effects in comparison to baseline production levels.

The 3.4 billion gallon/year scenario was viewed as an upper limit to possible ethanol industry expansion by 1992. Expansion of ethanol production to 3.4 billion gallons/year by 1992 may not be feasible, though, considering: 1) construction lead times required for new facilities, 2) the lead time for business decision makers to determine that they would invest in such facilities, and 3) the need for significant changes in the economic climate or in government incentives/programs to occur in the very near future in order to convince decision makers to invest. No specific policy action or change in market conditions is suggested to reach the specific production scenarios, nor are these production levels presented as goals. They are simply tools for illustrating and explaining ethanol's potential impacts at expanded levels of production for the future. Discussion of policy alternatives for encouraging the ethanol industry are confined to the Panel's summary and conclusions and are based on the study's findings on the potential costs and benefits of increased ethanol production.

PREFACE

The following report is based on an extensive review and analysis of available data and information on ethanol production and the U.S. energy situation, as well as a limited amount of new modeling of the impacts of increased levels of ethanol production. The Panel has primarily concentrated on explaining and clarifying issues and making informed judgments as to the impacts of ethanol on the U.S. This document is meant to serve as a policy-making tool, to help decision makers and the public gain a better understanding of the cost-effectiveness of ethanol fuel use in the U.S., by addressing the issues mandated in the Panel's enabling legislation. The seven subject areas which the enabling legislation directed the Panel to address involve a substantial number of interrelated issues that tend to overlap in some instances. For the sake of clarity and in order to improve public understanding of the interrelationships among the various issues, the Panel has organized its work on the separate issues in a logical format that addresses each subject in its proper context.

The report first presents summaries and conclusions, based on the report findings, in order to provide a direct, brief account of the results of the Panel's investigations and the actions the Panel feels are warranted given the findings presented in the report. Chapter 1 introduces the reader to the basic facts about the ethanol industry and the U.S. energy situation over the last 15 years. Chapter 2 addresses the technological and cost factors involved in ethanol production. Taken together, these first two chapters explain the ethanol industry and the energy markets and economics that affect ethanol production.

Chapter 3 addresses ethanol's close relationship with agriculture and the agricultural economy. It explains in brief the types of impacts and effects ethanol production has on agriculture, particularly in regard to corn production/surpluses and agricultural program costs. Chapter 4 explains ethanol's impacts on the environment, specifically on air quality. Finally, Chapter 5 discusses the crucial issue of energy security and ethanol's role ir assuring the U.S. of adequate, reliable supplies of energy.

In order to measure ethanol's impacts, three production scenarios were used to illustrate the type and magnitude of impacts ethanol could have on various aspects of the U.S. economy over the next 5 years. Each scenario's change in production is measured in terms of additions or subtractions from a baseline ethanol production level that increases from the current level of approximately 850 million gallons/year up to 1.1 billion gallons/year in 1992-93, a modest expansion rate considered reasonable if oil prices and government programs remain the same. Scenario 1 supposes a steady increase in ethanol production from the current 850 million gallons/year doubling to 1.7 billion gallons/year

SUMMARY AND CONCLUSIONS

Congress established the Panel to examine the cost-effectiveness of ethanol fuel production. The issues Congress wished to investigate covered a broad range of topics, including the technical and economic factors that influence ethanol production costs, as well as the impact of ethanol production on agricultural commodities, farm incomes and rural economies; the U.S. trade balance; the environment; and U.S. energy security. A combination of new investigation and review of existing research and analysis were used to examine these issues. Because of the constraints on time and resources inherent in such an investigation, some issues have been discussed in a qualitative manner and noted as areas warranting further research. Major issues that the Panel feels would warrant further examination include ethanol's impacts on state tax expenditures, on soybeans, and on consumers, as well as the actual costs and benefits of various incentives that would need to be increased or created to reach various levels of ethanol production. In addition, the Panel investigated a number of issues not specifically raised by the Panel's mandate, but which it believes to be important enough to bring to the attention of Congress and the government. The major conclusions and observations developed during the study are presented in the following discussion.

Chapter One -- Fuel Ethanol Industry Overview

The Panel has reviewed the ethanol industry's past and current development in order to assess the advances in ethanol technology, production, and marketing that have enabled the ethanol industry to achieve the significant growth it has experienced since 1980. The analysis is essentially a review of existing information on ethanol's history, the current status of the industry, foreign competition, fuel ethanol's current role in the U.S. energy market, and government support for fuel ethanol.

The Panel's investigation found that the fuel ethanol industry's steady growth has been supported by federal and/or state incentives. The Panel found that foreign ethanol imports had challenged the domestic industry in the past, but foreign competition is not expected to be significant in the near term with current tariffs. ***Fuel ethanol's role in the U.S. energy infrastructure has broadened from its sole use as a gasoline extender.*** Ethanol is increasingly recognized for its potential as a gasoline octane enhancer and as a means of improving air quality in some parts of the U.S. with high levels of carbon monoxide. These broader roles for ethanol provide an improved marketing outlook for fuel ethanol.

If the U.S. government expands support for ethanol fuels, the findings of this report provide important considerations for policy makers. *Incentives provided to date have been effective in encouraging ethanol production, but incentives must be reliable and consistent in order to induce the ethanol industry to continue or expand production, given an unstable energy market based on cartel-influenced oil prices.* The ethanol industry relies on federal and state support to remain viable in the face of such instability. While the marketing outlook for ethanol has improved with recognition of its octane and environmental benefits, these opportunities have only begun to be realized.

Chapter Two -- Fuel Ethanol Technology and Economics

The economics and cost of production for modern ethanol production facilities were evaluated by the Panel using original research and analysis techniques as well as reviewing existing information. Fuel ethanol feedstocks, processes, production cost factors, marketing, and gasoline-blending economics were all examined in order to provide the Panel with a comprehensive basis for assessing ethanol's economics.

The Panel concludes that corn is currently, and will probably remain, the predominant ethanol feedstock, with important contributions from several other grains and feedstocks. Large facilities, those with annual production capacities over 40 million gallons, account for most of U.S. ethanol production capacity; a relatively small number of companies and facilities produce most of the U.S.'s ethanol. Smaller facilities also play an increasingly important and viable role.

Increased production efficiency in the industry is likely with new processing innovations that could reduce the cost of ethanol in the near term. Currently, wet-milling technology has a slight cost advantage over dry-milling, but in the near future neither technology has a clear advantage for new capacity additions. Future industry expansion, if it is encouraged, is likely to occur in three basic stages: 1) expanding capacity at existing facilities and resuming production at temporarily closed facilities; 2) converting existing industrial facilities to ethanol production; and 3) constructing new facilities.

Current federal tax incentives (in combination with the volatility waiver for ethanol fuels) make ethanol blends a price-competitive gasoline option for consumers as well as a competitive octane enhancement option for refiners and gasoline blenders. Ethanol-blend marketing is regional in nature, due largely to variations in state tax incentives which inhibit the development of a broad-based national market for ethanol.

Congress and the federal government, in considering national ethanol policy, should examine issues such as research and development, technical information dissemination, and support for ethanol marketing opportunities. *First, further research and development into ethanol feedstocks and production technology could help the current and future ethanol industry to produce ethanol more efficiently and in greater quantities.* The use of improved corn strains offers opportunities for improving current ethanol output per bushel of input, while abundant cellulosic feedstocks (e.g., wood, plant stalks) could greatly expand the future ethanol feedstock supply. Innovations in conversion technologies have played an important role in ethanol's previous growth, and continued research could provide near-term improvements in ethanol technology and production economics. Research on cellulosic feedstock conversion could provide a future source of economic ethanol from abundant feedstocks.

Research into human consumption of ethanol by-products could also benefit the cost-competitiveness of the ethanol industry, as well as other industries that produce high-protein by-products that could be used by both U.S. and developing countries for food and livestock feed. Industrial and non-food uses of ethanol by-products would also be a useful area of research for diversifying the ethanol industry's markets and opening new outlets for U.S. agricultural products.

A substantial amount of research has been conducted on the effect of ethanol on automobile engines and driveability. All major manufacturers of automobiles sold in the U.S., including domestic and foreign automakers, cover under warranty the use of ethanol blends containing up to 10% ethanol. However, research on the effects of ethanol on small engines is still sparse; further research in this area is needed to adequately address the unresolved issues. In addition, disseminating to the public the results of research on both automobile and small engines would help alleviate unwarranted consumer concerns.

If ethanol is to be encouraged, it would be useful for the federal government to seek state cooperation in providing stable and consistent incentives for ethanol production across the U.S. This would help facilitate a nationwide market for ethanol that would be less concentrated in these states with the greatest incentives. Similar incentives in every state and locality would allow ethanol marketers to devote less time to tapping the most favorable incentives and more on promoting and distributing their product to the broadest market possible. Allowing proportionate excise tax exemptions for ethanol blends at other than 10% to achieve optimal octane enhancement could also improve ethanol's marketability.

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Chapter Three -- Ethanol Fuels and Agriculture

The impacts of ethanol production on corn, other feed grains, soybeans, and the rural and national economy were examined, and the following issues are discussed: 1) the economic effect of fuel ethanol production using U.S. corn as a feedstock; 2) tradeoffs between federal support for ethanol production and agricultural programs; 3) the effect of increasing ethanol production on the agricultural economy, including agricultural prices and farm income; and 4) the employment impacts of ethanol production.

Three alternative scenarios were used to illustrate the impacts of ethanol production. The scenarios represent ethanol-production levels of 1.7 billion gallons/year, 3.4 billion gallons/year, and no ethanol production, by 1993. These levels of production are not necessarily plausible or even possible; they are only illustrative tools used to represent the impacts of levels of production that might result from various policy options. Likewise, the Panel had no intention of recommending these production levels or measuring the direct costs in terms of increased federal and/or state support needed to achieve these levels of output.

The analysis done for the Panel found that ethanol will provide benefits to the agricultural sector in terms of higher prices for corn and other feed grains, increased farm income, and savings on agricultural program costs which would more than offset the current federal excise tax exemption costs for ethanol. Ethanol also produces benefits for rural economies that are under severe economic stress by generating jobs, personal income, and tax revenues in these localities. However, due to time and resource constraints, the specific actions necessary to further expand ethanol production from current levels were not analyzed (e.g., market changes, ethanol mandates, or increased government incentives). Thus, if increased government incentives are used, their costs would need to be assessed to determine if the savings to the government would offset the cost of increased support.

Some commodities, notably soybeans and other oilseeds, would be adversely affected by increased ethanol production. *Soybean impacts and options for alleviating adverse effects of ethanol production expansion on soybean markets are important areas where further research is required.* Farmers in the Corn Belt will likely be required to set aside less acreage in government programs and be able to raise more corn, thereby benefitting from expanded ethanol production. Farmers in other regions will not have this option. State tax incentives and possible adverse impacts on consumer, employment, and economic activity in other sectors of the economy were not examined. These factors reduce the net benefits of ethanol production, and warrant further examination. In reaching final conclusions about ethanol policy, these factors are important, but must also be compared with ethanol's intangible benefits for the environment, energy security, and rural economies.

In considering future ethanol policy, Congress and the federal government should weigh all the costs and benefits of ethanol production. Any programs to further encourage ethanol use should be combined with efforts to devise policies that will alleviate adverse impacts on farmers who grow crops such as soybeans--a major competitor with ethanol by-products. Adverse effects of ethanol support on the Highway Trust Fund must also be recognized and ways to reduce these adverse effects considered if national support for ethanol production becomes a long-term element of energy policy.

International trade is one of the most visible and important economic issues facing the world. Agricultural products and energy are of major importance to all countries, and agriculture is a high-priority issue in negotiations of the General Agreements on Tariffs and Trade (GATT). Most of the European Economic Community as well as Canada and Australia are considering ethanol fuel development. This could provide a partial solution to worldwide agricultural production overcapacity while providing the added benefit of decreasing the dangers of world reliance on imported oil.

Ethanol by-product and soybean meal export markets should also be an area of special emphasis if ethanol issues are pursued in trade negotiations. If ethanol production is increased, it is essential to expand export markets for protein by-products, particularly in developing countries. Ethanol production could provide substantial protein supplies for both human and livestock consumption throughout the world.

One perspective that must not be lost as the impact of ethanol on the agricultural sector is considered, is the long-term implications versus the near-term impacts. In an era of worldwide overproduction of grains, this excess production capacity is considered a burden to the trade and economic policies of many countries. Nontraditional industrial uses for grains should be viewed in the context of a tool to increase long-term demand. An increase in the long-term demand is the only permanent solution to the continuing high cost of supporting the farm sector.

Research and development efforts mentioned earlier in support of ethanol production technology and marketing also have positive implications for the agricultural sector, particularly development of new uses for ethanol by-products such as specialty chemical production, carbon dioxide cooling of beverages, and the expanded use of ethanol production as a step in food-processing waste treatment.

Chapter Four -- Air Quality Benefits of Ethanol-Blended Fuels

The Panel conducted an extensive and thorough review of ongoing research on the impact of ethanol-blended fuels on air quality. In particular, the pollutants carbon monoxide (CO) and ozone were examined, as well as nitrogen oxides (NO), aldehydes, and ethanol's effects on performance and materials compatibility characteristics in automobiles. The limited available research on small engines was also reviewed.

The Panel found that the use of ethanol blends has been proven to decrease CO emissions by between 10 to 30 percent (depending on the model year of the car) over vehicles fueled with straight gasoline. This decrease in CO emissions may contribute to attainment of the National Ambient Air Quality Standards (NAAQS) for CO in some areas of the country, and decrease CO levels in all other areas where ethanol blends are used extensively.

Blending ethanol with gasoline has been shown to raise the vapor pressure of the fuel over that of straight gasoline, resulting in increased evaporative hydrocarbon emissions. *This increase aggravates ozone attainment problems in areas where ethanol blends are used extensively, unless measures are taken to control evaporative emissions of automotive fuel or ethanol usage is restricted during the summer, in which case ethanol blends should not significantly affect ambient ozone levels.*

If Congress and the government choose to encourage increased ethanol production, ethanol's environmental benefits should be weighed. *In CO nonattainment areas ethanol can provide substantial air quality improvements, especially in winter months when CO problems are most severe and ozone levels are reduced.* In some cases, Congress may wish to encourage the use of ethanol-blended gasoline or programs to develop ethanol-fueled vehicle fleets as one measure of a city's commitment to attainment of air quality standards.

Further investigation of the volatility of ethanol blends and the resultant effect of increased ethanol production on evaporative emissions levels and ambient ozone concentrations would help to more accurately define the issue. If ethanol use is encouraged in areas with CO and ozone nonattainment problems, then regulatory strategies for control of hydrocarbon emissions from both mobile and stationary sources should be evaluated in order to produce the optimum mix of controls. Where possible, *policy options should be structured so as to offset ethanol's impact on ozone while maintaining ethanol's positive benefits for the environment, energy security, and agriculture.*

As mentioned earlier, further research is needed to clarify the effects of ethanol-blended fuels on small engines (e.g., lawnmowers and marine engines). Broader dissemination of the results of this research, in addition to the findings of the existing studies of ethanol's compatibility with automotive engines, is needed.

Chapter Five -- Ethanol and U.S. Energy Security

In examining the implications of ethanol for U.S. energy security, the Panel relied on recent investigations of the U.S. energy situation and then evaluated ethanol within the context of these earlier studies' conclusions.

The Panel found that there are many ways to achieve domestic energy security. No one approach by itself, including fuel ethanol production, will completely eliminate our reliance on imported petroleum. However, ethanol is one of a very few demonstrated, commercially-available, liquid-fuel alternatives. As a liquid fuel, ethanol displaces petroleum in a highly oil-dependent sector--transportation.

Ethanol is gradually being assimilated into the existing liquid fuel infrastructure and can also be integrated with other potential alternative liquid fuels. In addition, ethanol is produced from renewable, domestically grown feedstock that is not subject to foreign domination.

Ethanol's contribution to energy security is a crucial consideration in developing ethanol policy. *Congress and the government should be aware that the 1993 termination date for the ethanol excise tax exemption seriously inhibits further ethanol investment and also threatens the current ethanol infrastructure, as discussed earlier. Stable, long-term, consistent support for alternative fuel development is necessary if the industry is to continue.* Given the instability inherent in the current world oil market, the ethanol industry needs to be assured that its products will continue to receive the support essential to remain commercially viable, if Congress decides to maintain or expand ethanol use. With federal incentives set to expire in 1993, the necessary stability and consistency are currently lacking and discourage further expansion. Current ethanol tax incentives are unable to respond to wide fluctuations in world energy markets; providing more flexible support mechanisms that can adjust to such fluctuations would also increase the stability of ethanol development. There are many precedents for government support to evolving energy industries, and it seems reasonable to extend that kind of support to the ethanol industry.

In addition to the findings for the chapters discussed above, the Panel also examined several general issues that arose during the course of the investigation. In the course of the study the Panel has found that federal support for ethanol production comes from a variety of programs and agencies. This may be appropriate, given each program's particular concerns and expertise. *However, an ongoing industry/government effort to coordinate and improve the various federal efforts to support ethanol development (from R&D to loan guarantees and tax incentives) would be useful.* An advisory group could help improve both the effectiveness of government programs and industry's ability and willingness to make the best use of these programs. They could also disseminate information to industry and the public to increase awareness and utilization of developments in ethanol technology and use. *Expanding and revising previous or existing loan guarantee programs or creating new financing mechanisms for ethanol facilities could be considered in order to provide investors with the backing they need to develop and operate efficient, cost-competitive facilities.* Given improved coordination, industry government cooperation, and a serious commitment to maintaining consistent and adequate support for ethanol production, supporting construction of modern ethanol facilities could provide an effective means of encouraging increased, efficient ethanol production.

If Congress and the government choose to encourage greater ethanol production, the federal government could provide leadership by using ethanol-blended fuels to the maximum extent possible within government vehicle fleets. In formulating and implementing national policy, the government should seize opportunities to realize ethanol's benefits. *Improving coordination of existing programs and new research and development represent opportunities for government to provide the impetus needed to make ethanol an important contributor to national energy security.*

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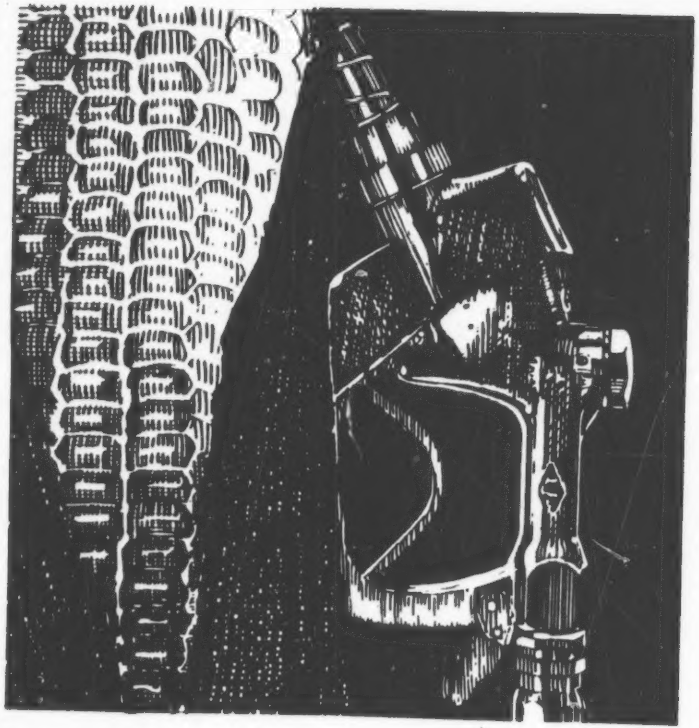
Fuel Ethanol and Agriculture: An Economic Assessment



SUMMARY

The Nation's alcohol fuels industry was developed in response to concern in the seventies that foreign nations could interrupt our oil supplies and disrupt our economy. Since fuel ethanol from renewable resources like grain and sugar crops can serve as a gasoline extender, major Government efforts were undertaken to stimulate this domestic industry. Since U.S. grain production exceeded demand in recent years, support for the ethanol industry was viewed as addressing two problems: (1) expanding a domestic fuel industry from renewable resources and (2) reducing Government commodity program costs by increasing demand for grain. In 1985, the industry produced some 625 million gallons of ethanol by converting about 240 million bushels of corn and other feedstocks.

This report examines the economics of ethanol production through 1995 and the impacts on farmers, consumers, and Government outlays for ethanol subsidies and agricultural price support programs.

The study used the USDA-ERS Food and Agricultural Policy Simulator Model (FAPSIM) in assessing the interaction of changing ethanol production levels on agricultural and food product demand and prices. The FAPSIM base case had ethanol production increasing from 595 million gallons in crop year 1985 to just over 1 billion gallons per year in crop year 1995. We examined one scenario where ethanol production doubled to 2 billion gallons per year in 1995, and a second scenario where ethanol production declined to zero gallons per year in 1995. These two scenarios were considered extremes which should bracket the most likely outcome.

Among our findings:

- The ethanol industry cannot survive during the period studied without massive Government subsidies, given the outlook for petroleum prices. Costs of producing ethanol in 1986 are estimated to be $1.41-$1.52 per gallon while the wholesale price of gasoline is projected to be $0.55 per gallon, and gasoline blenders value ethanol at $0.20-$0.25 per gallon less than gasoline.
- Unless the Federal subsidies which are scheduled to expire December 31, 1992, are extended, fuel ethanol production likely will be terminated or sharply curtailed after 1992.
- If large enough subsidies are provided, additional ethanol production would increase net farm income by an estimated $2.2 billion over the 1986-94 period, or $0.58 per additional gallon of ethanol. However, a much larger amount (some $1.25-$1.35 per gallon) would go for energy, chemicals, labor, and overhead costs incurred in converting corn to ethanol.
- Subsidies required to sustain the ethanol industry will offset any savings in agricultural commodity programs resulting from the increased demand for corn.
- Corn prices would increase by $0.02-$0.04 per bushel for each 100 million-bushel increase in ethanol-induced demand for corn. However, soybean prices would fall by about $0.04 per bushel and soybean meal prices would fall by $0.12-$0.15 per hundredweight.
- Higher corn prices from additional ethanol-induced demand would increase the cost of producing beef, pork, and poultry. Consumer food expenditures would rise by $8.6 billion, or an average of $2.29 for each additional gallon of ethanol produced.
- When all the costs and benefits are tallied, the Government, taxpayers, and consumers together would lose $6.1-$7.2 billion or $1.61-$1.92 per additional gallon produced during the 1986-94 period if ethanol subsidies were increased enough to prompt the ethanol industry to produce 2 billion gallons in 1995. Conversely, if ethanol production falls to zero, they would save some $6.8-$8.9 billion, or $1.35-$1.76 per gallon not produced.
- Possible improvements in technology through 1995 are unlikely to reduce ethanol production costs enough to significantly alter these conclusions. Nor would the conclusions be altered materially if ethanol producers could get by with existing subsidies.
- Subsidized ethanol production is a very inefficient way to raise farm income. It would be much more economical to burn straight gasoline in our automobiles and pay farmers a direct subsidy equal to the amount they would receive as a result of ethanol production.

Appendix B

Review Article on Ethanol from Non-Food Biomass

Large-Scale Fuel Ethanol From Lignocellulose:
Potential, Economics, and Research Priorities

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DRAFT

ABSTRACT

Ethanol produced from lignocellulose is considered as a large scale transportation fuel. Five key issues are identified and considered in relation to the status of current and foreseeable technology. These are: conversion and production energy balances, suitability of ethanol as a transportation fuel, air quality impacts, raw material supply, and cost. Energy balances and fuel characteristics appear to be consistent with large scale use of ethanol produced from lignocellulose. Local and global air quality benefits are expected to accompany use of lignocellulose ethanol. Raw material availability is examined for wastes and for trees and grasses grown as energy crops. Ethanol production levels appear unlikely to be limited by raw material availability as long as economic and other factors are sufficiently favorable to justify allocation of land for this use. Projected ethanol production costs based on current directions of research would allow neat ethanol to become competitive with gasoline by the year 2000 according to current oil price predictions. Biological process steps have the largest contribution to overall costs, are among the least developed aspects of the technology, and appear to have the greatest potential for improvement. Research priorities are discussed.

INTRODUCTION

Practical production of ethanol from lignocellulosic materials has been a goal of researchers since the mid seventies, and has been a particular focus at the Biotechnology for Fuels and Chemicals Symposia. Lignocellulosic materials are so called because they contain cellulose, a carbohydrate composed of beta-linked glucose subunits, hemicellulose, a carbohydrate composed of xylose and other sugars, and lignin, a heterogeneous aromatic polymer[1].

Lignocellulosic materials are a distinct class of raw material from corn, which has a carbohydrate fraction consisting of starch rather than cellulose. Examples of lignocellulosic materials are trees, grass, and waste paper and cardboard. Both corn and lignocellulose are plant material of recent photosynthetic origin, and can be referred to as biomass. Conversion of corn and lesser amounts of grains to ethanol is the basis for a substantial industry in the U.S. at present [2,3]. Ethanol produced from these sources is used as a gasoline additive which raises the octane of gasoline. Approximately 7% of the total motor gasoline used in the U.S. is blended with ethanol [4]. The economics of corn-derived ethanol are currently dependent on federal subsidies, and the value of processing residues as feeds [2,3]. Brazil has the largest alcohol fuel industry in the world, with sugar cane as the raw material [5]. Lignocellulose is not currently a raw material for commercial ethanol production on a significant scale.

The motivations for considering lignocellulose as a raw material are that it is inexpensive, plentiful, and renewable. Lignocellulose is also recalcitrant to biological conversion relative to soluble 6-carbon sugars such as those which can be produced from corn or sugar cane. Ethanol is an attractive product of lignocellulose processing in that it can be produced in near theoretical yields from many carbohydrates by biological fermentation. Furthermore, ethanol is a versatile compound which can be used as a raw material for the chemical process industry [6,7], an octane enhancing fuel additive either as ethanol per se or ethyl-tert butyl ether (ETBE)[8], or as a neat fuel. Various uses for ethanol are listed in Table 1, along with estimates of the relative value for utilization as a chemical feedstock, blending fuel, or neat fuel. As addressed in more detail below, both strategic and trade balance considerations are driving forces for developing a large-scale fuel ethanol industry.

A particular advantage of fuel ethanol produced from biomass is the potential for air pollution abatement. Alcohol fuels, including both ethanol and methanol, have the potential to lower levels of key urban air pollutants. In addition, the lignocellulose/ethanol fuel cycle is distinctive among transportation fuel options in that its use is accompanied by no net contribution to the greenhouse effect [14].

Production of ethanol from lignocellulose was an intense focus of research during the early eighties, motivated by the high cost of oil. Attention and activity relative to lignocellulose ethanol has declined markedly during the 1980s, prompting an exodus of researchers from the field, and drastic cuts in remaining research programs. As presented in Figure 1, the current DOE budget for biomass production and conversion to fuels is more than 6-fold smaller than in 1980 [15]. The decreased interest and support for lignocellulose ethanol is the result of a combination of factors, including a precipitous drop in oil prices, failure to achieve commercial success in the short timeframes some anticipated, and changing priorities at the Federal level.

This paper will consider the large-scale use of ethanol in neat (unblended) form in the United States. As may be seen from Table 1, utilization as a neat fuel will almost certainly achieve market penetration at a later time than other uses because of the lower value of ethanol in this application. However, neat fuel is clearly the largest scale use of ethanol, and can therefore be expected to have the greatest impact relative to the economic, strategic, and environmental issues which are motivating factors for ethanol utilization in general. In this sense, large scale use of neat ethanol is the ultimate goal of research on lignocellulose ethanol. In addition, identifying constraints and opportunities for large scale fuel use may be helpful in formulating research goals and evaluating progress. Finally, examination of the goal of large scale fuel ethanol utilization may be useful in determining the allocation of effort and resources that this fuel path deserves.

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BACKGROUND

Important perspectives from which to view the prospect of large scale use of fuel ethanol include those related to environmental, energy, and economic issues.

At present, concern over local and global air pollution are the major factors prompting interest in alternative fuels. The local air pollution issue centers around high levels of ozone and carbon monoxide in many cities. Over 75 areas in the U.S. exceed National Ambient Air Quality Standards for Ozone and/or CO [16]. The EPA[16] forecasts that carbon monoxide levels are expected to fall somewhat due to turnover of the transportation fleet. The number of areas out of compliance with respect to ozone is expected to decline somewhat until 1995, but to increase thereafter.

1988 saw a major increase in concern over global warming due to the "greenhouse effect". According to the statement of the conference on The Changing Atmosphere held in Toronto, the ultimate consequences of atmospheric changes "could be second only to a global nuclear war" [17]. Numerous articles in scientific journals and periodicals have chronicled the debate over whether warming has begun and what extent of warming may be anticipated [18-23]. In a draft report on Policy Options for Stabilizing Global Climate, the EPA [21,23] states that the scientific community agrees that significant global warming caused by greenhouse emissions will occur throughout the next century. The report concludes further that 57% of greenhouse gas emissions and greenhouse warming is due to energy use and production, with the next largest contribution at 17%.

Energy production and utilization in the United States is a very large scale enterprise. As events during the last two decades have demonstrated, changes in energy prices and availability have profound influences on our economy. Oil imports comprise about a quarter of the foreign trade deficit[13,24], petroleum expenditures are about 2% of the GNP[13,24]. A consequence of the energy-economy interplay is that alternative fuels will be strongly favored if they can offer lower cost, but will be unlikely to find favor if they do not.

Table 2 presents data for the four major energy carriers utilized in the U.S. It may be seen that petroleum supplies the largest share of total energy utilized and has the highest fraction imported, both by significant margins. Furthermore, the domestic supply of conventional petroleum is the most limited of the four major carriers. The values given for the ratio of total recoverable reserves: annual utilization rate represent the number of years required to exhaust reserves if we used only our own resources. Imports will lengthen the time before reserves are exhausted. It may be noted that total recoverable reserves are substantially larger than economically recoverable reserves, and also that the values presented in Table 2 do not include unconventional resources of oil and gas.

The virtually complete dependence of the transportation sector on petroleum is a singular phenomenon in the U.S. energy picture. Whereas all other sectors have substantial ability to switch fuels in the event of a supply disruption, the transportation sector does not [27]. World petroleum resources are concentrated in the politically unstable middle east[27,28]. Thus petroleum resources, and in particular use of petroleum by the transportation sector, are by far the major energy security issues from a strategic point of view. Energy consumption by the transportation sector totalled 21 quads in 1988 [13], about a quarter of total energy consumption. Of total transportation sector energy use, motor gasoline comprised 14 quads or about two thirds.

Chevron[29] has forecast the future availability and price of petroleum well into the twenty-first century. These predictions are summarized in Figure 2. According to Chevron, oil exploration and production are expected to become progressively more expensive. Thus the already prominent role of petroleum in the national economy can be expected to increase significantly. Although the U.S. is expected to import well over half its oil by 2000[27,28], with the bulk of this coming from OPEC [27], the era of OPEC dominance of world oil markets is expected by both Chevron and the DOE[27] to be with us for little more than another decade.

An additional major change is anticipated shortly after 2000, that of satisfying needs we presently meet with conventional petroleum by other resources. The shift from conventional petroleum is consistent with the distinctly limited size of domestic conventional supplies (see table 2). In the period 2000-2030, Chevron predicts that petroleum produced by enhanced oil recovery will be available at a price of 25-40 1987$/barrel. This price prediction is consistent with the expectations of the American Petroleum Institute[28], which forecasts a price of 31$ per barrel in 2000.

Present and anticipated oil prices provide a context in which to consider the selling price required for neat ethanol to compete with gasoline on a non-subsidized basis for use as a transportation fuel. As presented in Table 3, the required wholesale selling price for ethanol is 46.2 cents/gal at today's oil and gasoline prices, and 76 cents at prices predicted in 2000.

KEY ISSUES

In light of the discussion above as well as general considerations pertaining to fuel use, some key issues for the development of lignocellulose ethanol can be identified (see Table 4). For lignocellulose fuel ethanol to be viable, significant net energy must be available in the course of producing lignocellulose and conversion to ethanol. Equally obvious is the fact that ethanol must be a good transportation fuel. Favorable impact with respect to air pollution and other environmental factors would make ethanol, or any other fuel, more attractive, while unfavorable impacts are strong disadvantages given the already high level of concern over this issue. A fourth key issue is whether enough raw material is available to make a difference. Finally, the issue of cost is inescapable.

TECHNOLOGY STATUS

Energy balance. The energy balance of fuel ethanol production from lignocellulose is not likely to constrain the development of this technology. Estimates for the energy required for lignocellulose production are typically about 15% of the energy content of the ethanol which could be produced therefrom for high productivity culture methods 30,31,32,33 and less for lower productivity methods. These estimates include energy required for planting, cultivation, fertilization, harvest, chipping, transportation, and in one case 32 an allowance for equipment depreciation. The energetics of lignocellulose conversion to ethanol are similarly clear cut. Combustion of unfermented residues, principally lignin, produces energy in excess of processing requirements for present process designs with a wood feedstock 34. Most designs make use of the excess energy to generate electricity in a cogenerative fashion. Because of the availability of lignin to provide energy for the process, theoretical conversion of carbohydrate is possible from an energetic perspective. The overall thermal efficiency of ethanol production from lignocellulose for a process with high yields is in the range of 45 - 60%, depending on the lignin content of the raw material.

The higher thermal efficiency of fuel ethanol relative to gasoline is discussed below. It may be noted here that the 20% greater thermal efficiency of ethanol implies that 1 quad of ethanol displaces 1.25 quads of gasoline. The added efficiency of utilizing the fuel ethanol compensates for the 15% energy loss in lignocellulose production.

Fuel properties. Alcohol transportation fuel began with the use of alcohol in the invention of the internal combustion engine by Nikolas Otto in 1897[5]. Alcohol fuels are different from, and in many respects superior to, gasoline as a fuel for spark-ignited engines 16,35,36. Ethanol has very similar fuel properties to methanol 36,37,38. Combustion of ethanol in internal combustion engines designed for alcohols will give higher thermal efficiency and power, than use of gasoline in present engines, while performance is generally comparable to gasoline in non-optimized engines 35-38. A significant development for the use of alcohol fuels is the fuel flexible vehicle 27,36, which is capable of operating on any mix of ethanol, methanol, or gasoline. Table 5 summarizes performance parameters for fuel ethanol relative to gasoline. Problematic cold starting and

fuel maldistribution are generally thought to require some modification, but to be small issues, particularly for alcohol-devoted engines 35,36,41.

The thermal efficiency of fuel ethanol utilization is a particularly important aspect of engine performance. Efficiency, along with energy density, determines the volume of ethanol required to deliver the same work as a gallon of gasoline, and hence the required price at which ethanol becomes competitive relative to gasoline. A range of thermal efficiency improvements for neat ethanol relative to gasoline are frequently quoted 10,27, with typical values of 10-20% . Values are often cited without specifying whether the engine is designed for alcohols. Comparison is further complicated by the variability of gasoline and the sensitivity of efficiency to operating variables. Kampen 12 estimates volumetric fuel consumption for ethanol-devoted engines at 1.25 times that of a gasoline engine to travel the same distance, thus implying that 1 gallon of ethanol is equivalent to 0.8 gallons of gasoline in terms of its ability to do work. This corresponds to a 17.6% greater thermal efficiency (using energy density ratios given by Kampen). Bernhardt 11 states that an optimally designed alcohol vehicle would have about 75 - 80% of the energy requirement of a vehicle designed for standard gasoline, or 80-85% of the energy required for high test gasoline. These values correspond to thermal efficiency increases of 25-33% relative to standard gas, and 17.6 to 25% relative to high test. In terms of price, Bernhardt estimates that pure ethanol is equivalent to high test gasoline at an ethanol price 75% of the gasoline price on a mass basis. This corresponds to 81% on a volume basis (gasoline mass density from 28, gas and ethanol energy densities based on the lower heating values given by OTA), implying a 24.4% higher thermal efficiency.

Research on methanol utilization has proceeded more rapidly than on ethanol utilization of late 16,36, primarily because of the availability of inexpensive methanol produced from natural gas. Ford 36 has found volumetric mileage on methanol to be 0.6 to 0.7 that of gasoline. This corresponds to methanol having a 25 - 46% higher thermal efficiency. These high efficiency increases are consistent with values presented by the EPA for fuel efficiency increases for methanol relative to gasoline. Gray [42] reports small efficiency increases for use of methanol without modification and for making the engine smaller due to increased power, a further efficiency increase up to about 17% for compression ratio increases, an efficiency increase up to a total of about 27% if lean combustion is also employed, and finally a higher efficiency up to about 45% made possible by fuel dissociation. Based on older work [12,37], efficiency increases possible with ethanol are approximately two-thirds to three-quarters those possible with methanol.

Use of alcohols in compression-ignited diesel-type engines has been investigated to a much smaller extent than spark-ignited engines; use in jet engines has not been studied at all to the author's knowledge. In light of the dominant place of gasoline in the transportation sector and the relatively advanced state of engine research for spark-ignited engines, the focus for fuel ethanol use is very likely to be cars and light-duty trucks for some time.

Impact on local and global air pollution. Table 6 presents the anticipated effect of fuel ethanol utilization on emissions of important pollutants. As with performance, evaluation of emissions is complicated by the dependence on operating variables. The only class of pollutant emissions significantly higher for alcohol fuels are aldehydes, which are produced in 3-6 times larger amounts relative to gasoline[44]. Several sources are optimistic about the use of catalytic converters to remove aldehydes and unburned fuel [10,35,42], however Ford[36] is more cautious.

Not withstanding the uncertainty over aldehyde emissions, the EPA[38] believes that significant long-term environmental benefits are available from using ethanol, and also methanol and compressed natural gas, as pure fuels in engines designed to take full advantage of the excellent combustion properties of these fuels. Table 7 presents estimated emission reduction potential for alcohol fuels in light-duty vehicles. The prospect of emission reductions of this magnitude has been sufficient motivation for the state of California to give very serious consideration to the widespread substitution of methanol for gasoline [45,46]. The choice of methanol was decided on the basis of current economics rather than performance or emissions [36,38]. Although methanol can be produced thermochemically from biomass [47], economics strongly favor production from natural gas

The lignocellulose-fuel ethanol cycle is represented in Figure 3. The cycle results in the net conversion of solar energy to engine work, and in no net generation of CO_2 [14] The release of CO_2 upon combustion is exactly balanced by the removal of CO_2 by photosynthesis. The stable cycle involving present-day photosynthesis, lignocellulose conversion to ethanol, and ethanol combustion can be contrasted to the situation for fossil fuel combustion. Also the products of photosynthesis, fossil fuels originate from plant matter which accumulated incrementally over millennia. The relatively sudden release of this by fuel combustion over the course of about a century results in increased atmospheric CO_2 concentrations. The EPA draft report on Policy Options for Stabilizing Global Climate [23] recognizes the potential of biomass fuels to cut emissions of greenhouse gasses.

Raw material availability. Sources of lignocellulose can be divided into wastes from processes undertaken for a purpose other than energy production, and plants grown for the purpose of fuel production. The latter category may in turn be divided into conventional forestry, and short rotation intensive culture [48].

Table 8 presents estimates for the ethanol production potential from various sources of waste materials. The values given are based on estimates for collectible wastes compiled by the author [33]. The total ethanol production potential from wastes is five quads, with 37.9% of the potential from agricultural wastes, 31.3% from forestry wastes, 11.8% from urban wastes, and 19% from miscellaneous other wastes. The ethanol production potential is based on a process obtaining high yields from both 6-carbon and 5-carbon sugars with some allowance for processing losses, incomplete fermentation, and the production of microbial biomass. Details of the calculation procedure are in [33] and the legend of Table 12. The total of 5 quads as ethanol presented in Table 8 may be compared to the value of 13.8 quads of potential energy available as wastes given by Klass and Sen [19]. These values are of comparable magnitude if the thermal efficiency of conversion to ethanol (discussed above) is taken into account.

Utilization of some of the materials included in Table 8 would require development of technology beyond its present state. Currently available organisms are much less efficient at utilizing 5-carbon sugars such as xylose than 6-carbon sugars [34]. Xylose fermentation is discussed in detail below. A further point is that about two thirds of the forestry wastes are softwoods [10], which are not as susceptible to biological attack as hardwoods [50]. Whereas current research directions for efficient xylose utilization appear promising [34], utilization of softwoods may be a more difficult problem. Subtraction of softwood forestry wastes from the values presented in Table 8 would put the total waste potential at 4 quads.

Plants grown for energy production (energy crops) require allocation of land for this use. Categories of land that might be used for lignocellulose production include forest land which is not potential crop land, idled crop land, or potential cropland presently in other uses, which include some forests. Of these, idled land is by far the most variable. Figure 4 presents the amount of crop land idled by federal programs over the last ten years, and the ethanol which could be produced from this land via short rotation intensive culture and a conversion process with high-yields. It may be noted that herbaceous energy crops grown in a one-year rotation are promising for short rotation intensive culture (SRIC) [31]. Such crops could be responsive to the widely varying amount of land in the idled crop land category. The ethanol production potential of idled crop land varies from 0 to 3.6 quads at present SRIC productivities, and 0 to 5.6 quads at 1996 projected SRIC productivity.

Idled crop land results from the federal government paying farmers not to plant land under the auspices of the annual acreage reduction program, and the conservation reserve program [52]. The land in these programs has amounted to over 4% of the land area of the lower 48 states during the last two years. Idled acreage in the conservation reserve program (CRP) was 31% of total idled land in 1988, the highest figure since the program's inception in 1986. The annual cost of the CRP alone was 3.8 billion dollars in 1988. The CRP was created to convert highly erodible land to conserving uses [52]. 95% of the land enrolled in the CRP has been planted in grasses or trees [52], the two major energy crops considered for SRIC. Many lignocellulosic energy crops significantly reduce land erodibility relative to row crops [31]. Although harvesting from land in the CRP is not presently allowed, Ranney et al [31] note that SRIC crops would be an excellent compromise for obtaining economic returns from land while providing needed soil protection.

Table 9 presents land area requirements and ethanol production potential for various sources of lignocellulose. In addition to wastes and idled cropland already discussed, lignocellulose production by conventional forestry on forestland (excluding potential cropland), and SRIC on potential cropland are also considered. The values for forestland are based on the amount estimated for energy production by the Office of Technology Assessment [10], which corresponds to 28% of commercial forestland. Values given for potential cropland are for the entire land in this category with no allowance for availability. The ethanol production potential from wastes and all three land categories varies from 7.9 to 8.9 quads, with land devoted to unmanaged forests, and 18 to 23.6 quads, with all suitable land used for SRIC with projected productivities. The variability in these values reflects that of idled crop land.

The ethanol production potentials listed in Table 9 are very large, several amounting to substantially more than the 14 quads currently used as motor gasoline. The overall potential is reduced significantly if SRIC is not employed. While potential crop land may not become completely available for energy crops, this is not necessary in order that a very substantial contribution be made. For example, utilization of wastes, and 50% of available forestland, 50% of potential cropland, and the mean idled crop land employing SRIC at projected productivities where possible would yield 15.4 quads on a total of 8.5% of the land area of the lower 48 states. In considering ethanol production potential and land requirements, it is important to keep in mind the dynamic nature of present cropland requirements and energy use - neither of these is in any sense fixed. Cropland requirements could decrease substantially due to increased agricultural productivity, or to a shift in diet away from animal products. Approximately 80% of U.S. cropland is presently used to produce animal feed [53]. Alternatively, attractive export markets could increase cropland requirements for purposes other than energy production. Similarly, changes in transportation fuel demand may well occur due to changes in fuel price, fleet efficiency, population, or driving habits [54].

While the ethanol production potentials listed in Table 9 are very large, the same can be said of the land areas required. The author is not in a position to evaluate the full implications and likelihood of such major shifts in land use. While a definitive analysis of this issue would certainly be welcome, the ultimate answer may not come until we have experience with the environmental, economic, social and other impacts associated with lignocellulose conversion to ethanol on a modest scale. It may be noted in passing that an amount of land corresponding to 29% of the area of the lower 48 states is currently leased for oil and gas exploration in these states [28].

Ethanol production from corn currently plays a significant role as a source of fuel ethanol and an alternative market for the agricultural sector [2,3,4], and may well continue to do so into the future. However, the ethanol production potential of the entire U.S. corn crop is an order of magnitude lower than the values presented in Table 9. Production of ethanol from corn at a volume commensurate with the current crop would be expected to saturate feed by-product markets, upon which favorable economics depend [10].

Cost. In terms of the current state of technology development, the most critical cost issues concern conversion of the raw material to ethanol.

Four principle approaches have evolved for biologically converting lignocellulose to ethanol [33,55]: separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), direct microbial conversion (DMC), and processes involving lignocellulose solubilization by acid hydrolysis. Acid hydrolysis-based processes are considered to be less promising in the long term [56], and will not be considered further here. Flow diagrams for SHF, SSF, and DMC are presented in Figures 5A, 5B, and 5C respectively. The differences between these processes stem from the biological steps, and specifically the manner in which lignocellulose is hydrolyzed. Whereas SHF involves sequential enzyme production, hydrolysis, and fermentation, SSF involves consolidation of hydrolysis and fermentation into a single step. DMC represents a further step in the direction of consolidation in that production of the hydrolytic enzyme cellulase, lignocellulose hydrolysis, and fermentation to ethanol all occur in a single vessel. DMC is distinguished from the other processes by the cellulase production and fermentation are carried out by the same organism.

Research on SHF and SSF processes is being pursued by the Solar Energy Research Institute (SERI) as well as others. SSF is currently favored over SHF processes by SERI and seems likely to remain so [55]. DMC processes are the least well developed, but have the lowest potential cost on a conceptual level at least. Advantages of DMC processes include no diversion of substrate for enzyme production, no added cost for enzyme production, and compatible enzymes and fermentation systems. Although the cost advantages of the properties of DMC systems are very significant [33], detailed cost analyses at the level of those available for SSF and SHF have not been performed for DMC. Two approaches are promising for development of DMC processes: 1) to broaden the substrate range of good ethanol producers such as yeast or *Zymomonas mobilis* using recombinant DNA techniques; or 2) to improve the ethanol-producing ability of organisms with broad substrate ranges such as thermophilic bacteria using metabolic and/or genetic manipulation.

Table 10 presents the author's estimates for the stage of development for the various steps in the conversion of lignocellulose to ethanol. The least well developed steps are the biological steps, whereas utilities and waste treatment are the best developed steps.

Table 11 presents economics for SHF and SSF process designs according to the Solar Energy Research Institute. SSF has an 88 cent per gallon cost advantage over SHF primarily because the amount of enzyme required is reduced due to lessened inhibition by hydrolysis products [55]. Although xylose conversion systems are not very well developed, the incentive to utilize xylose and obtain high yields is so strong that substantial savings can be realized even with non-optimal biocatalysts [34]. A production cost of $1.35/gal ethanol via an SSF process with xylose utilized represents the present state of the art. In 1980 the price was almost $4/gal [14], and progress has been more rapidly of late. SERI projects a cost of 75 cents per gallon based on current research directions and a low-lignin feedstock. Ethanol at this price would be competitive for use as a neat fuel with anticipated gasoline prices in 2000 (see Table 3). Table 11 also shows the dominant contribution of biological steps to the cost of production, and the correlation between reduced overall cost and reduced cost of biological steps. The economic importance of the biological steps (Table 11) together with their poorly developed status (Table 10) makes the biological steps good candidates for future cost reductions, and a logical priority for research. Contributions to improving biological steps are likely to come from approaches based on both engineering and life sciences.

Ethanol yield, ethanol concentration, and volumetric productivity are important parameters in determining production costs. All three are profoundly influenced by properties of the biological system.

Ethanol yield (mass ethanol per mass raw material) is determined by several factors These include: the substrate utilizing capability of the fermentation system (e.g. with respect to xylose); the end-product metabolism of the fermentation system (e.g. whether products other than ethanol are formed); the ability of the cellulase to hydrolyze the raw material; the ability of the pretreatment process to make the raw material accessible to enzymes; the process design (e.g. DMC increases yield because substrate is not diverted to enzyme production); and the raw material (e.g. softwoods are more difficult to convert than hardwoods). Cost sensitivity studies have consistently shown yield to be a critical parameter[55,58] This arises because the influence of yield is pervasive. Process steps

affected include all aspects of substrate production, pretreatment, and fermentation, utilities and waste treatment. Certain fixed costs associated with each of these steps are typically related to the amount of material processed rather than the amount of product made, thus the amount of product made can be increased with little incremental expense. Critical issues with respect to ethanol yield are pentose utilization, elimination of by-products (for DMC), improving conversion of softwoods, and utilizing lignin.

High yields from xylose and other 5-carbon (pentose) sugars is in all probability a requirement for an economic process implemented on a large scale. Table 12 presents data for the carbohydrate composition and potential ethanol yield for corn and representative lignocellulosic raw materials. If xylose, which exists in insoluble form as pentan, is converted, then corn, grass, and hardwood have virtually the same ethanol yield. In the case of forage grass, the contribution of pentan to the overall ethanol yield is 42%. Pentan also makes a very significant contribution (30%) to the potential yield from municipal solid waste. Typical yield values are 85-90% of theoretical for cellulose, and 70% of theoretical for xylose [34,55].

The ethanol concentration which can be practically achieved in the fermentation system is determined by the tolerance of the fermentation system, the tolerance of cellulase to ethanol and sugars (the latter limits ethanol concentration in SHF designs [55]), the limited concentrations of lignocellulosic slurries, and the distillation system. Rheological constraints limit lignocellulose slurries to about 12 wt% carbohydrate, which even with theoretical yields would produce 6 wt% ethanol. Higher ethanol concentrations could be obtained, if tolerance permitted, by fermenting pentoses as well as hexoses. Ethanol concentration is an important issue primarily in relation to the fermentation and distillation steps. Continuous removal of ethanol from the fermentor can limit the effects of concentration to the distillation system [33] The sensitivity of distillation costs to ethanol concentration will depend on the distillation system employed. Typical ethanol concentrations are 4.5% for SSF [55], 2.25% for SHF [55], and 1.5-2% for DMC [33] These values are in the cost-sensitive region for nearly all distillation technologies, and may be compared to 7% or more for ethanol production from corn [59]. Energy efficient processes employing heat pumps and/or columns linked in a multi-effect manner have been proposed [60-62], which can decrease the concentration sensitivity of distillation costs and energy requirements. Because distillation requires steam, utility-related costs are affected by ethanol concentration as well as costs for fermentation and distillation costs. Critical issues concerning concentration are understanding the cell biology of ethanol tolerance, and increasing research and full-scale experience with energy efficient distillation processes and continuous ethanol removal.

Volumetric productivity (mass ethanol per bioreactor volume per unit time) is determined by the rate of substrate utilization by cellulase (the primary factor for insoluble raw material fraction), the rate of substrate utilization by the fermentation system (the primary factor for the soluble fraction), the ethanol concentration, and the bioreactor design. Primary economic impacts are on the saccharification/fermentation steps, and utilities. A substantial portion of total energy requirements in current SSF designs is devoted to bioreactor stirring [55]. Saccharification and fermentation are carried out in a batch reactor with a one week cycle time[55]. Productivities for both the saccharification/fermentation step and for xylose conversion are exceedingly low at 0.27 and 0.17 g ethanol/L*hr respectively. These values may be compared to conventional process for ethanol production from 6-carbon hexose sugars, about 3 g/l*hr [3], and high productivity processes which can achieve over 100 g/l*hr [63,64]. The saccharification and fermentation step per se is the single largest cost in the entire SSF process by more than a factor of two. Thus both the incentive and the potential improvements in the productivity area seem particularly significant. A promising approach is reactor design for conversion of lignocellulosic substrates. This is an understudied and underexploited area in the author's opinion, perhaps in part because SERI's designs did not include fermentation in the presence of solids until the adoption of SSF in 1988. Progress in reactor designs will

probably involve continuous processing, and may also include differential retention and/or plug-flow distribution of raw material within the bioreactor. The potential of continuous processing is suggested by preliminary results in the author's lab in which high hydrolysis yields are obtained from pretreated hardwood in a 12 hour residence time using a simple well mixed continuously fed reactor.

SUMMARY AND CONCLUSIONS

Of the major energy sources used in the U.S., petroleum has the smallest domestic supply, and the greatest reliance on imports. The transportation sector accounts for roughly two thirds of petroleum consumption in the U.S., has far greater dependence on petroleum than other energy sectors, and has the least flexibility to switch to alternative fuels. In addition, use of petroleum-based transportation fuels is a factor contributing to local air pollution and the greenhouse gas emissions. These factors make providing for future transportation fuel demand a particularly critical aspect of national energy planning and environmental protection.

Energy balance considerations, fuel suitability, and anticipated air quality impacts are all consistent with the use of neat ethanol as a large scale transportation fuel.

Projected ethanol production costs based on current directions of research would allow neat ethanol to become competitive with gasoline by the year 2000 according to current oil price predictions. In spite of a decade of intensive research, conversion of lignocellulose to ethanol must be regarded as a moderately well developed technology at best. Aspects of process configuration, biocatalyst selection, and other basic issues are still very much in a state of flux. The potential cost reductions through research driven technological improvements appear to be great. Examples of research directions particularly likely to be productive are reactor design for systems accomplishing the hydrolysis and fermentation of solid substrates, more efficient utilization of xylose, and development of direct microbial conversion systems. Substantial cost savings are also available at the development level, for example minimization of mixing energy requirements in a saccharification/fermentation reactor.

If favorable economics allowed the growth of a large scale lignocellulose-based fuel ethanol industry, a number of beneficial effects can be anticipated. These include a more favorable foreign trade balance, enhanced energy security, improved urban air quality, reduced emissions of greenhouse gasses overall and no net emissions from the portion of the transportation sector powered by ethanol, and a major new crop for an agricultural sector which has been depressed for most of a decade and has more productive capacity than can be supported by present demand.

Ethanol production levels appear unlikely to be limited by raw material availability as long as the economic and other factors are sufficiently favorable to justify allocation of land for this use. Continued development of short rotation intensive culture technology is highly desirable in order to minimize land requirements for raw material production.

Several applications other than neat fuel production with significant impacts in their own right can serve as proving grounds for processes converting lignocellulose to ethanol. These include co-production of ethanol with other chemicals, use of ethanol as a chemical feedstock, and producing ethanol as a by-product in the treatment of the non-plastic organic fraction of municipal solid waste.

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TABLE 1. END USES FOR ETHANOL

USE	VALUE	REFERENCE
CHEMICAL FEEDSTOCK	> FUEL VALUE	9
BLENDING FUEL		
1. DIRECT	1.7 - 2.5 x CRUDE PRICE (~1.0 - 1.5 x GASOLINE)[1]	10
2. INDIRECT (ETBE)		8
NEAT FUEL	0.8 x GASOLINE	11,12

[1] With crude oil at 14.71 $/barrel; (1988) the wholesale value of ethanol as an octane enhancer is 59.5 to 87.5 cents/gal according to the OTA[10] formula. This may be compared to the 1988 average wholesale price of 57.7 cents/gal for gasoline (oil and gas prices from[13]).

TABLE 2. SELECTED DATA FOR UNITED STATES ENERGY UTILIZATION[1]

ENERGY SOURCE	ANNUAL CONSUMPTION (QUADS)[2]	SECTOR WITH GREATEST DEPENDENCE[3]	% IMPORTED[2]	ESTIMATED TOTAL RECOVERABLE RESERVES[4] UTILIZATION RATE
PETROLEUM	33.9	TRANSPORTATION (97%)	37	17 YEARS
COAL	18.8	UTILITIES (55%)	-13	>1000 YEARS
NATURAL GAS	18.6	RES./COMMERCIAL (32%)	6.6	39 YEARS
NUCLEAR	5.7	UTILITIES (20%)	-	.5
OTHER	2.9			
TOTAL	79.9			

[1] ALL DATA FOR 1988.

[2] DATA FROM [13]

[3] DATA FROM [13]; INCLUDES INDIRECT CONTRIBUTION AS FUELS FOR ELECTRIC POWER GENERATION.

[4] OIL AND NATURAL GAS RESERVES FROM [25] AND ARE FOR CONVENTIONAL OIL AND GAS. TOTAL RECOVERABLE RESERVES ARE THE SUM OF MEASURED, INDICATED, INFERRED, AND UNDISCOVERED RESERVES; ECONOMICALLY RECOVERABLE RESERVES ARE A SMALLER QUANTITY. COAL RESERVES FROM [26] CORRECTED FOR CONSUMPTION UP TO THE PRESENT. UTILIZATION RATES FROM EIA.

TABLE 3. REQUIRED PRICE OF ETHANOL TO BE COMPETITIVE AS A NEAT FUEL.

	CRUDE PRICE[1] (\$/BARREL)	WHOLESALE GAS PRICE (CENTS/GAL)	REQUIRED ETHANOL PRICE (WHOLESALE, CENTS/GAL)[4]
1988	14.71	57.7[2]	46.2
2000	31	~95[3]	76.0

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1 1988: FROM [13]; 2000: FROM [28]

2 FROM [13]

3 IN 1982, CRUDE OIL SOLD FOR 31.87 \$/BARREL, AND THE WHOLESALE GAS PRICE WAS 97.3 CENTS/GAL [13]. 95 CENTS PER GALLON IS ALSO CONSISTENT WITH THE PRESENT INCREMENT OF ABOUT 9\$/BARREL AS THE ADDED VALUE OF GASOLINE RELATIVE TO CRUDE OIL.

4 BASED ON AN ETHANOL:GASOLINE EQUIVALENCE RATIO OF 0.8 (SEE TEXT).

TABLE 4. KEY ISSUES FOR FUEL ETHANOL PRODUCTION FROM LIGNOCELLULOSE

ENERGETICS OF THE LIGNOCELLULOSE/ETHANOL FUEL CYCLE

FUEL CHARACTERISTICS

AIR POLLUTION AND OTHER ENVIRONMENTAL IMPACTS

IS THERE ENOUGH RAW MATERIAL TO MAKE A DIFFERENCE?

WHAT WILL IT COST?

TABLE 5. PERFORMANCE PARAMETERS FOR FUEL ETHANOL RELATIVE TO GASOLINE[1]

PARAMETER	EFFECT	PROPERTY GIVING RISE TO EFFECT	REFERENCE
EQUIVALENCE RATIO[2]	LOWER	LOWER LEAN FLAMABILITY LIMIT	12,37,39,40
COMPRESSION RATIO	HIGHER	HIGHER OCTANE	12,37,39
THERMAL EFFICIENCY	HIGHER (10-20%+)	CHEMICAL PROPERTIES[3] LEANER A/F RATIOS HIGHER COMPRESSION RATIOS	11,12,35,37
COLD STARTS	DIFFICULT	HIGHER HEAT OF VAPORIZATION	35
FUEL MALDISTRIBUTION	INCREASED	HIGHER VOLUMETRIC FLOWS, HIGHER HEAT OF VAPORIZATION	35

[1] Statements are for neat ethanol in an engine designed for this fuel . Some benefits may cancel or diminish others. For example: higher compression ratios increase efficiency while also increasing NOx emissions [35,38] and lower equivalance ratios [39].

[2] Equivalence ratio = (stoichiometric A:F ratio)/(actual A:F ratio).

[3] Increased efficiency is observed without changing the equivalence ratio or the compression ratio [37,39]. This arises primarily from higher heats of vaporization and faster flame temperature [35].

TABLE 6. EMMISION PARAMETERS FOR FUEL ETHANOL RELATIVE TO GASOLINE[1]

PARAMETER	EFFECT	PROPERTY GIVING RISE TO EFFECT	REFERENCE
NO_x	EQUAL OR LOWER	LOWER COMBUSTION TEMPERATURES, LEANER A/F RATIOS	12,16,37,38
CO	EQUAL OR LOWER	LEANER A/F RATIOS	16,37
VOC (evaporative)	LOWER	LOWER VAPOR PRESSURE	38
VOC (exhaust)	SIMILAR OR HIGHER AMOUNTS, HIGHER ALDEHYDES, LOWER PHOTOCHEMICAL REACTIVITY	MANY	37,38,43,44

[1] Statements are for neat ethanol in an engine designed for this fuel . Some benefits may cancel or diminish others. For example: higher compression ratios increase efficiency while also increasing NO_x emissions [35,38] and lower equivalance ratios [39].

TABLE 7. ESTIMATED EMISSION REDUCTION POTENTIAL FOR ALCOHOL FUELS IN LIGHT-DUTY VEHICLES[1]

TECHNOLOGY	ESTIMATED EMISSION REDUCTION POTENTIAL		
	VOC	CO	NOx
CURRENT (FFV)	20-50%	0	0
ADVANCED[2]	85-95%	30-90%	0

[1] Data from the [16] for vehicles meeting current standards, and operated on methanol. Presentation with reference to "alcohol fuels" is justified because EPA "believes that the use of pure ethanol as a motor fuel would offer the same type of emission benefits as methanol" [38].

[2] Advanced technology refers to engines designed for alcohol fuels.

TABLE 8. ESTIMATED ETHANOL PRODUCTION POTENTIAL FROM WASTE MATERIALS[1]

WASTE SOURCE	ETHANOL PRODUCTION POTENTIAL	
	QUADS	% TOTAL
AGRICULTURAL	1.9	37.9
FORESTRY	1.6	31.3
MSW	0.6	11.8
OTHER	1.0	19.0
TOTAL	5.0[2]	100

[1] DATA ESTIMATED FROM SOURCES GIVING DATA FOR COLLECTIBLE WASTES COMPILED BY LYND [33].

[2] INDIVIDUAL POTENTIALS DO NOT ADD TO TOTAL POTENTIAL, AND DO NOT CORRESPOND EXACTLY TO THE % VALUES, BECAUSE OF ROUND-OFF.

TABLE 9. LAND AREA REQUIREMENTS AND ETHANOL PRODUCTION POTENTIAL FOR LIGNOCELLULOSE SOURCES

SOURCE OF MATERIAL	LAND AREA		ETHANOL PRODUCTION POTENTIAL (QUADS)[1]			
	10^6Ha	% lower 48	UNMANAGED FOREST	MANAGED CONVENTIONAL FOREST	SRIC, 1987 AVERAGE PRODUCTIVITY	SRIC, 1996 AVERAGE PRODUCTIVITY
WASTES[2]	None	None	5	5	5	5
FORESTLAND[3]	39	4.9	1.1	2.2	-	-
CROPLAND[4]						
A. IDLED	0 - 32	0 - 4.1	0 - 1.0	0 - 1.9	0 - 3.6	0 - 5.6
B. POTENTIAL	62	8.0	1.8	3.6	7.0	10.8
TOTALS[5]	101 - 103	12.9 - 17	7.9 - 8.9	10.8 - 12.7	14.2 - 17.8	18 - 23.6

[1] A FRACTIONAL MASS CONVERSION OF BIOMASS TO ETHANOL OF 0.34 IS USED, WHICH IS EQUALLY APPLICABLE FOR TREES AND GRASS (SEE [33]). VALUES USED FOR BIOMASS PRODUCTIVITY (Mg/Ha*Yr) ARE AS FOLLOWS: UNMANAGED FOREST, 3.4 [48]; MANAGED FOREST, 6.66 [10]; SRIC 1987 AVERAGE, 13 [31]; SRIC 1996 AVERAGE 20 [31].

[2] FROM [33]

[3] LAND VALUES ARE FOR FOREST LAND AVAILABLE FOR ENERGY PRODUCTION EXCLUDING POTENTIAL CROPLAND. THE DATA IS INFERRED FROM [10] AS FOLLOWS. OTA ESTIMATES THAT THE TOTAL NET PROEDUCTION POTENTIAL OF U.S. COMMERICAL FOREST LAND IS EQUIVALENT TO 18 - 36 QUADS, AND THE TOTAL ENERGY POTENTIAL OF THIS LAND AT 5 - 10 QUADS OR 27.8% OF THE PRODUCTION POTENTIAL. 27.8% OF COMMERCIAL FOREST LAND IS 53 million Ha. THE VALUE OF 39 IS OBTAINED BY SUBTRACTING THE 16.6 million Ha OF POTENTIAL CROPLAND PRESENTLY IN FOREST [51] TO AVOID DOUBLE-COUNTING.

[4] IDLED CROPLAND FROM [52], POTENTIAL CROPLAND FROM [51].

[5] 2.2 QUADS IS ADDED TO THE LAST TWO COLUMNS REFLECTING THE CONTRIBUTION OF MANAGED CONVENTIONAL FORESTS.

TABLE 10. ESTIMATED STAGE OF DEVELOPMENT FOR STEPS IN THE CONVERSION OF LIGNOCELLULOSE TO ETHANOL

PROCESS STEP	RESEARCH			PILOT	COMMERCIAL
	FUNDAMENTAL	APPLIED	PRE-PILOT		
BIOMASS PRODUCTION	**	*	*	**	**
PRETREATMENT	*	**	**	*	*
ENZYME PRODUCTION	*	**	*		(*)[1]
SSF	**	**	*	(*)	
XYLOSE FERMENTATION	**	**			
DMC	**	*			
DISTILLATION		*	*	*	*
WASTE TREATMENT					*
UTILITIES					*
RESIDUE PROCESSING				*	*

* = SOME ACTIVITY
** = MAJOR FOCUS OF ACTIVITY

[1] CELLULASE IS PRODUCED COMMERICIALLY BUT COMMERICAL DEVELOPMENT HAS FOCUSED ON APPLICATIONS OTHER THAN WOOD HYDROLYSIS.

TABLE II. ECONOMICS OF RECENT PROCESS DESIGNS FOR ETHANOL PRODUCTION FROM LIGNOCELLULOSE

	SHF(1986)[1]	SSF(1988)[2]	SSF+XYLOSE(1989)[3]	SSF+ XYLOSE PROJECTED[4]
COST OF PRODUCTION ($/gal)				
WOOD	0.82	0.68	0.52	0.29
OTHER OPERATING	0.79	0.48	0.39	0.25
CAPITAL	1.05	0.62	0.44	0.22
TOTAL	2.66	1.78	1.35	0.75
STEPS WITH LARGEST COST (relative to cost of production)				
BIOLOGICAL (Enzyme production, hydrolysis and fermentation)	55%	33%	29%	
NEXT LARGEST (utilities)	14%	18%	12%	

[1] FROM WRIGHT [55], BASED ON RESULTS OF WRIGHT ET AL [58]

[2] FROM WRIGHT [55]

[3] FROM HINMAN ET AL [34] AND N.D. HINMAN (PERSONAL COMMUNICATION)

TABLE 12. HIGH ETHANOL YIELDS FOR BIOLOGICAL PROCESSING OF LIGNOCELLULOSIC SUBSTRATES DEPEND ON PENTOSE UTILIZATION[1]

RAW MATERIAL	HEXAN		PENTAN		TOTAL SUGARS	
	Wt %	POTENTIAL ETHANOL YIELD[2]	Wt %	POTENTIAL ETHANOL YIELD	Wt %[3]	POTENTIAL ETHANOL YIELD
CORN	72	33.8	0	0	80.0	33.8
HARDWOOD	53.3	25.1	18	8.7	79.7	33.8
FORAGE GRASS	42.0	19.7	30	14.4	80.8	34.1
MSW	37.6	17.7	16	7.7	60.0	25.4

[1] DATA FROM SOURCES COMPILED IN [33]

[2] POTENTIAL ETHANOL YIELD IS CALCULATED PER UNIT LIGNOCELLULOSE AS FOLLOWS: YIELD PER LIGNOCELLULOSE, Y_L = TSF x f x Y_E. WHERE TSF = TOTAL SUGAR FRACTION = (180/162)*FRACTION HEXAN + (150/132)*FRACTION PENTAN, WHICH ALLOWS FOR THE WATER OF HYDROLYSIS. f = FRACTION OF TOTAL SUGARS FERMENTED, WHICH MAY BE < 1 DUE TO EITHER PROCESSING LOSSES OR INCOMPLETE FERMENTATION. Y_E = ETHANOL YIELD PER SUGAR FERMENTED. THE ETHANOL PRODUCTION POTENTIAL IS CALCULATED ASSUMING THAT f = 0.9, AND $Y_E = 0.47$. THE THEORETICAL VALUE OF Y_E IS 0.51, HOWEVER CELL PRODUCTION TYPICALLY LOWERS THIS SOMEWHAT.

[3] TOTAL SUGARS ARE NOT THE SUM OF THE HEXAN AND PENTAN FRACTIONS DUE THE WATER OF HYDROLYSIS (SEE ABOVE)

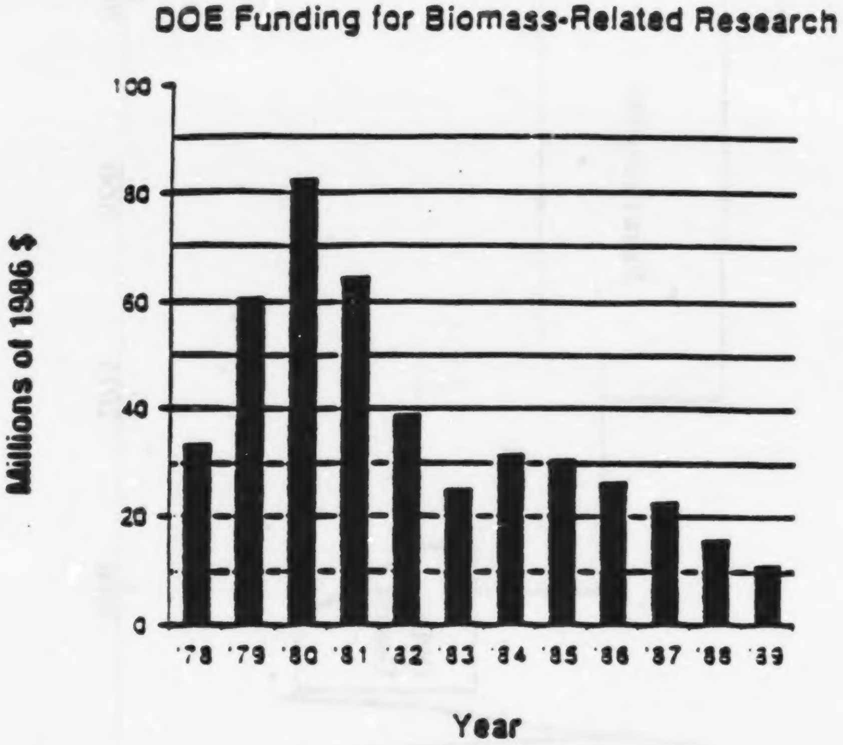


Figure 1. Data from [15].

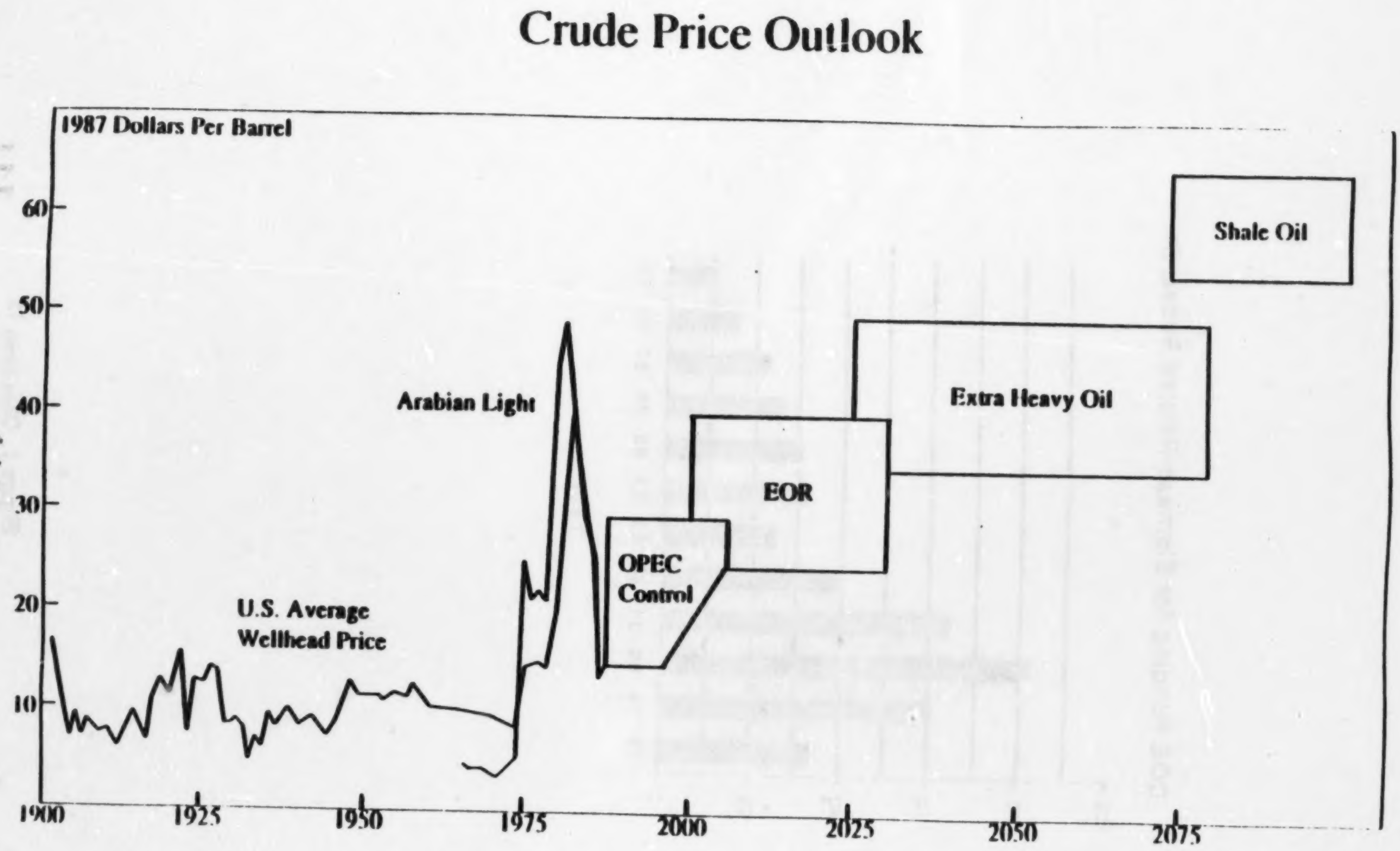

Crude Price Outlook

Figure 2. Data from[29].

Material and Energy Flows for Production and Utilization of Fuel Alcohol from Biomass

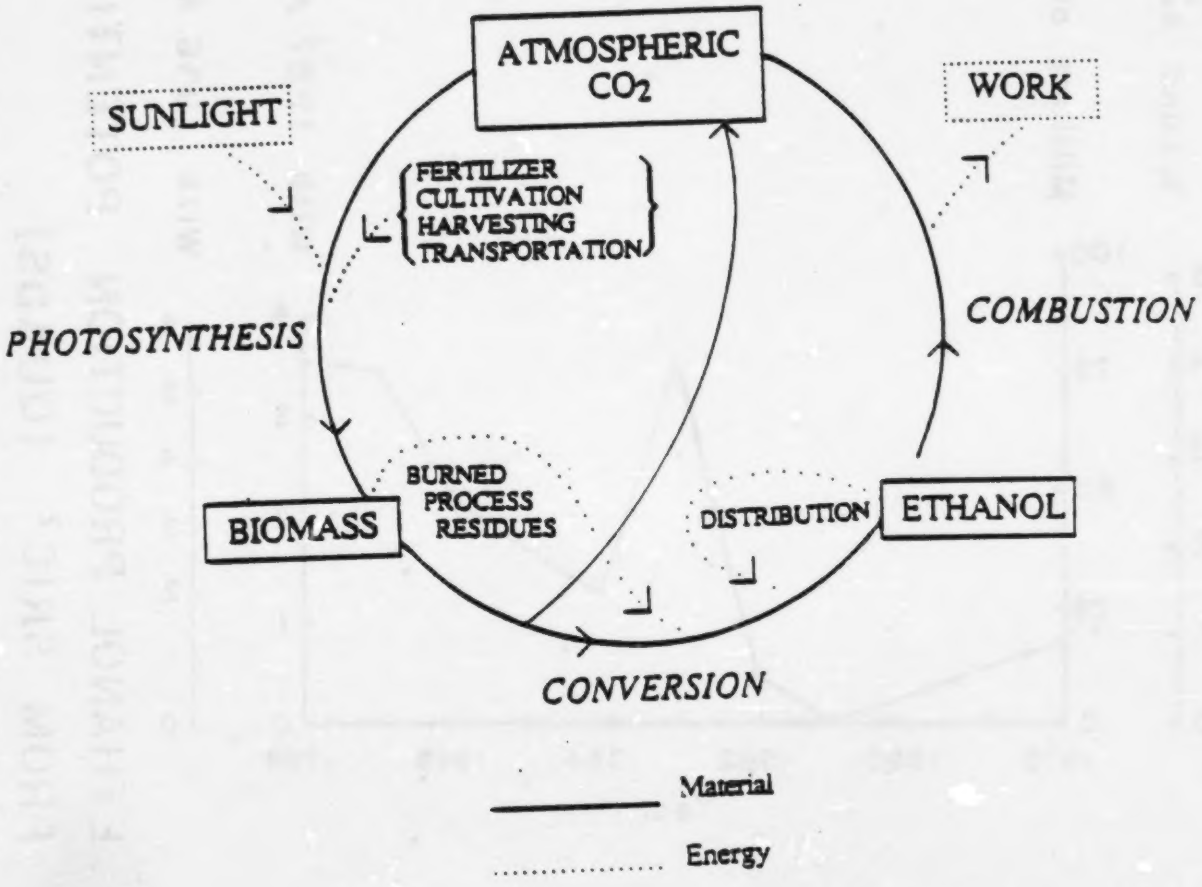
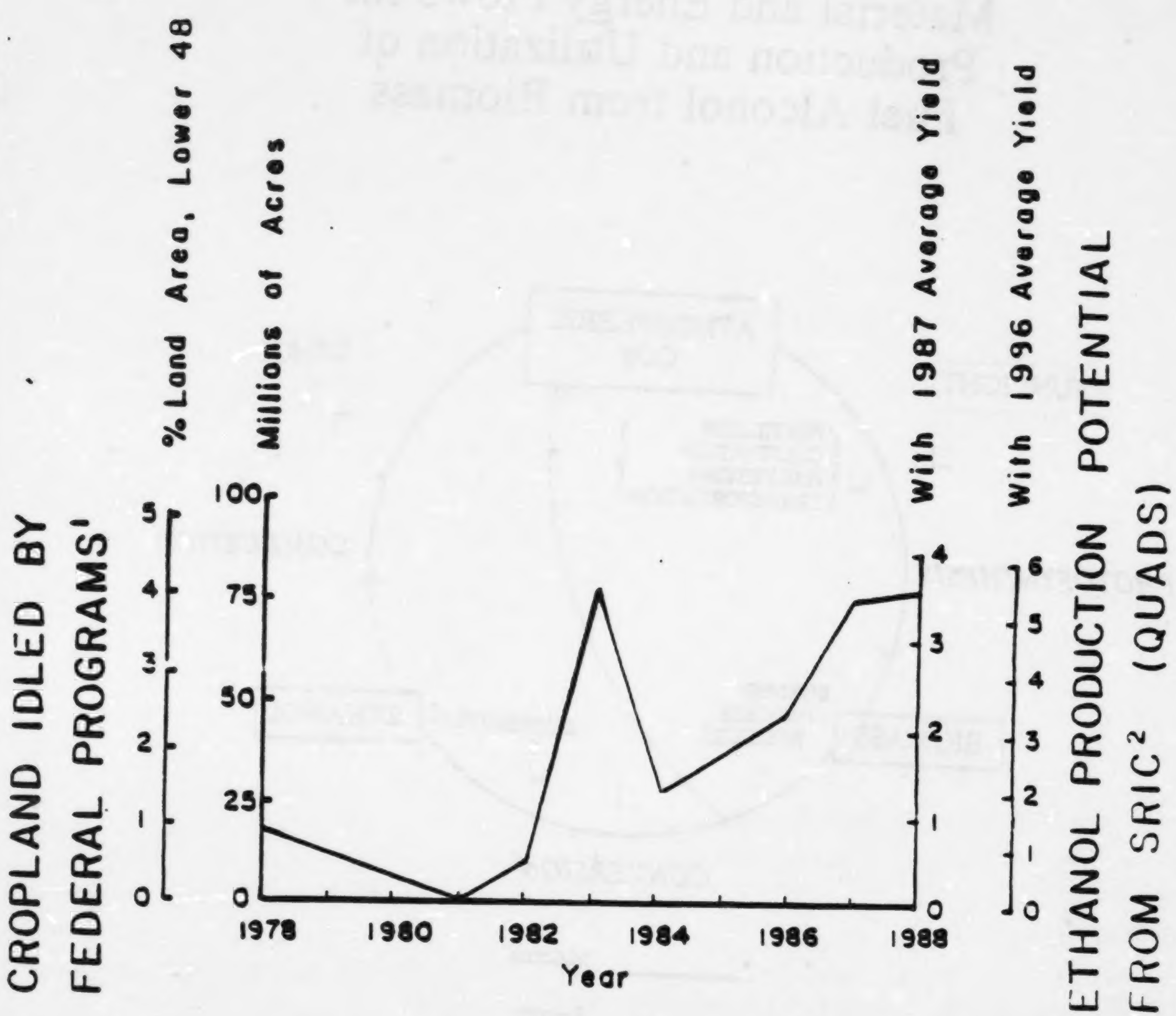

ATMOSPHERIC CO_2
SUNLIGHT
WORK
FERTILIZER
CULTIVATION
HARVESTING
TRANSPORTATION
PHOTOSYNTHESIS
COMBUSTION
BURNED PROCESS RESIDUES
DISTRIBUTION
BIOMASS
ETHANOL
CONVERSION
Material
Energy

Figure 3.



1 Annual acreage reduction and conservation reserve programs; data from USDA (1988)

2 1996 yields projected, biomass productivity from Ranney et al. (1987), convers

(1988)

Figure 4

Separate Hydrolysis and Fermentation[1]

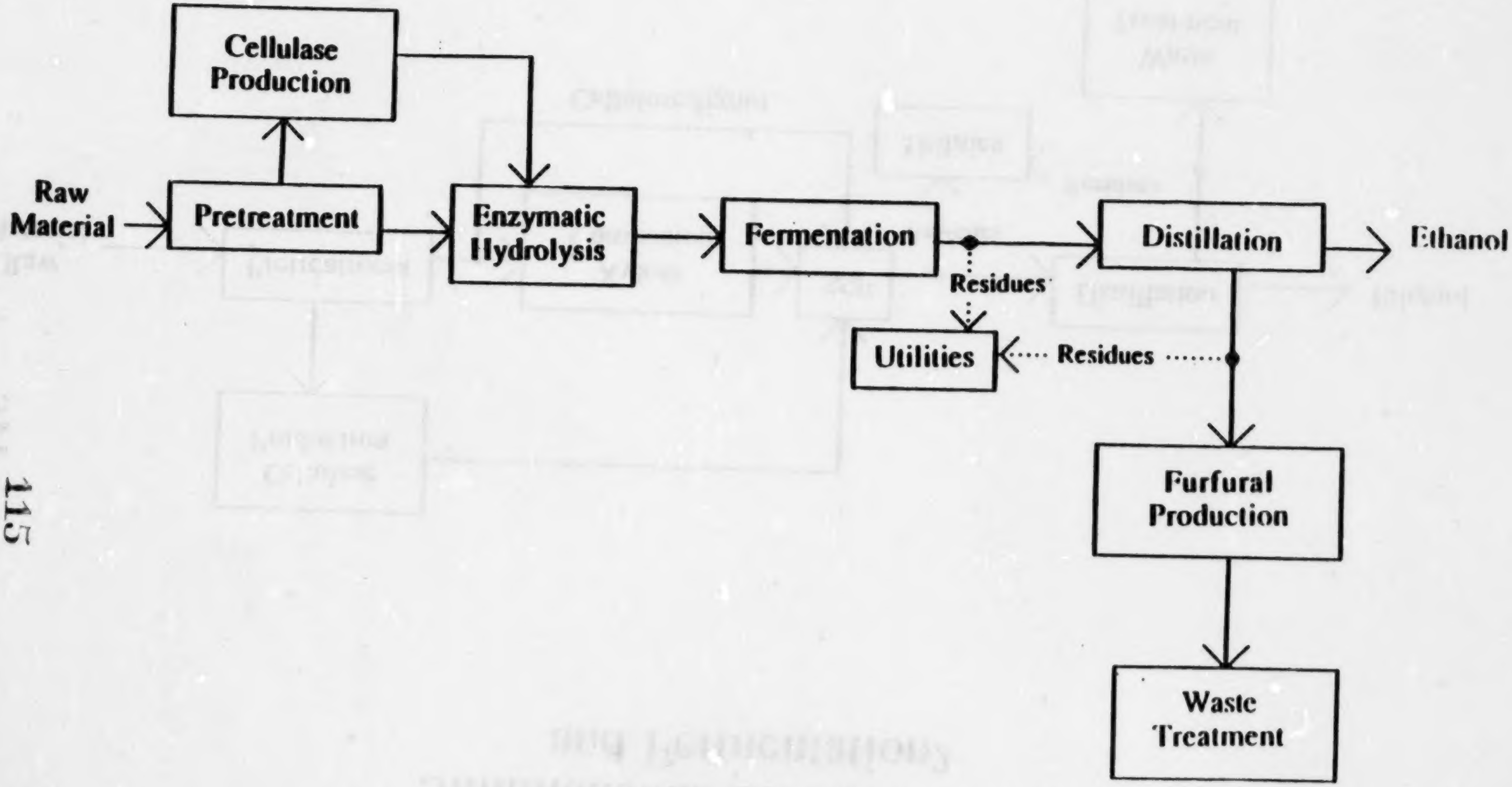

Raw Material
Pretreatment
Cellulase Production
Enzymatic Hydrolysis
Fermentation
Residues
Utilities
Residues
Distillation
Ethanol
Furfural Production
Waste Treatment

Figure 5A

[1] Adapted from Chem Systems (1984)

Simultaneous Saccharification and Fermentation[2]

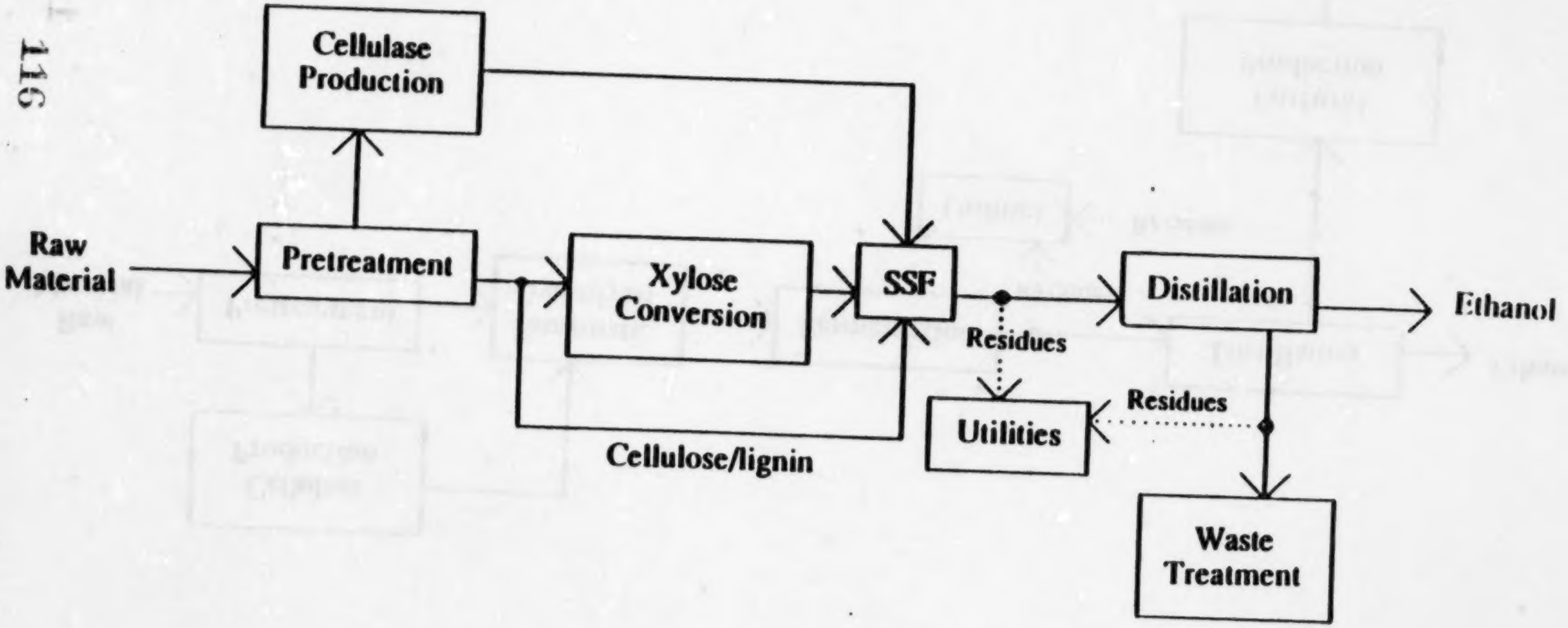

Raw Material
Pretreatment
Cellulase Production
Xylose Conversion
Cellulose/lignin
SSF
Residues
Utilities
Residues
Distillation
Ethanol
Waste Treatment

Figure 5B.

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[2] Adapted from Hinman et al (1989)

Direct Microbial Conversion

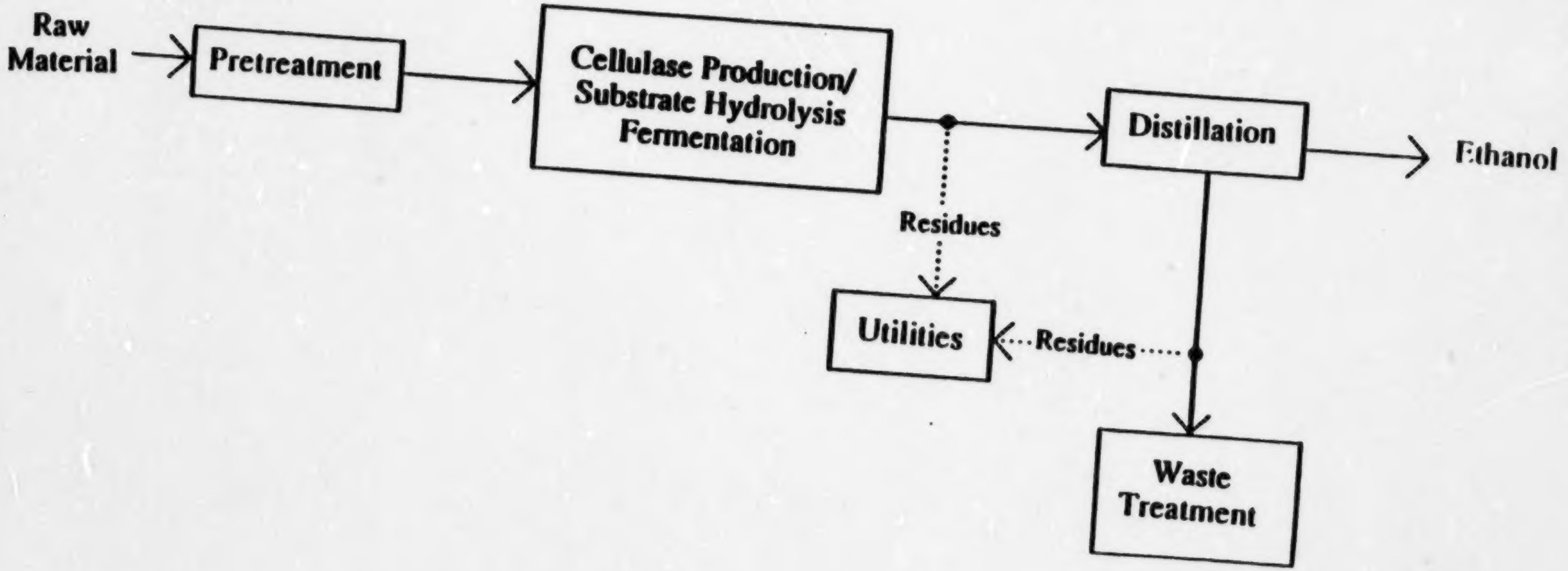
Raw Material
Pretreatment
Cellulase Production/ Substrate Hydrolysis Fermentation
Residues
Utilities
Distillation
Ethanol
Residues
Waste Treatment

Figure 5C.

Appendix C

Memo on Potential Ethanol Engine Efficiency

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR MICHIGAN 48105

DEC 1 1989

OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Cost Estimate for Ethanol Gasoline-Equivalent Price

FROM: Loren R. Washburn, Mechanical Engineer
Standards Development and Support Branch

TO: Charles L. Gray, Jr., Director
Emission Control Technology Division

THRU: Richard A. Rykowski, Senior Project Manager
Standards Development and Support Branch

Chester J. France, Chief
Standards Development and Support Branch

The August 1989 Special Report on Methanol as an Automotive Fuel projected a total retail and total gasoline equivalent retail price for methanol.[1] Following the same methodology as was used in that report, this memo presents a first pass at estimating the costs associated with ethanol (both E85 and E100). Previously estimated ethanol production costs are used to estimate the final price at the pump. A projected vehicle cost difference for ethanol vehicles will also be given.

SUMMARY

Compared to methanol, ethanol should provide similar vehicle efficiency improvements over gasoline. The efficiency improvement for a FFV using E85 was estimated to be 2.5 percent, which is half of the estimated M85 FFV efficiency improvement in the Methanol Report. The same efficiency improvement of 30 percent estimated for a dedicated M100 vehicle in the Methanol Report was also estimated in this memo for a dedicated E100 vehicle. Based on these efficiency estimates and assuming the plant gate price for ethanol to be between $1.00 and $1.50, the gasoline equivalent price was estimated to range from $1.19 to $1.81 per gallon for E85 and from $0.99 to $1.59 per gallon for E100 in a dedicated ethanol vehicle. These estimates include the effect of a 60 cent per gallon blending tax credit and a gasoline price from low crude.

Since, basically the same engine design would be used for both ethanol and methanol, with some modifications, the same vehicle costs should be realized for ethanol and methanol. The Methanol Report estimates a $300 increase per FFV and no increase for a dedicated methanol vehicle, which was also estimated for ethanol.

ANALYSIS OF ETHANOL COST

Methodology:

The gasoline equivalent retail price is determined by applying the subsidy to the plant gate price and then adding the distribution costs, service station markup, and taxes, which results in the total ethanol retail price. The gasoline equivalent ratio is then applied to this retail price to determine the total gasoline equivalent ethanol retail price. The gasoline equivalent ratio factors in the difference between the number of gallons of fuel required for ethanol to travel the same distance as gasoline. This ratio is determined by the fuel's energy content and the engine efficiencies.

Plant Gate Price:

The plant gate price of ethanol produced in the U.S. is assumed to be $1.00 to $1.50 per gallon. The price is dependent on the production facility which will depend on the demand. Currently, ethanol can be produced at current facilities, but if the demand became higher than current facilities could produce, new facilities would result in higher costs.

A subsidy for the producers of ethanol is applied, which will decrease the price to $0.60 to $1.10 per gallon.* Also, the price of E85 is determined by blending in gasoline at a price of 68.6 cents per gallon (low crude at $20/bbl), which results in a price of $0.61 to $1.04 per gallon of E85.[1]

Distribution, Markup, and Taxes:

Assuming only a regional distribution of ethanol to Midwestern severe ozone non-attainment areas (i.e., Chicago and Milwaukee), the distribution costs should be low. As with methanol, pipelines or waterways would be used to the deliver the fuel to the terminals; the trucking costs would be minimized by short, optimized trips. Therefore, the costs would be the same as methanol, 3 cents per gallon.

---

* The blending tax credit of 60 cents per gallon was reduced by the corporate tax rate, assumed to be 34 percent.

The service station markup for ethanol should be set in order for the stations to receive the same revenue per mile driven as they do now for gasoline. Since ethanol requires more gallons per mile, the markup would be less than the 9 cent per gallon markup for gasoline. The gasoline equivalent ratio (discussed below) is between 1.37 and 1.40 for E85 and between 1.15 and 1.50 for E100, so the estimated markups range from 6 cents to 9 cents.

Taxes are based on an equivalent BTU basis. Therefore, the ethanol per gallon tax is two-thirds of the gasoline tax. With the introduction of the more efficient E100 vehicles, however, this would not maintain a "revenue-neutral" program since the efficient vehicles will use fewer gallons of ethanol per mile. The loss in revenue could be recovered by increasing the taxes on ethanol accordingly or increasing the taxes on gasoline. The latter option would provide an economic benefit to the users of ethanol and, since more total miles will be driven by gasoline vehicles (assuming 30 percent alternative fuel vehicles), the increase in gasoline taxes could be spread out among the larger number of gasoline vehicle miles. As in the methanol study, though, no increase is included in either the ethanol or gasoline tax.

As Table 1 shows, the sum of the estimated costs for distribution, markup, and taxes is 26 cents to 28 cents per gallon for both E85 and E100. Therefore, the cost of ethanol at the pump would be between $0.87 and $1.32 for E85 and between $0.86 and $1.38 for E100.

Ethanol Fuel Vehicle Efficiency:

Ethanol has about two-thirds of the energy per gallon as contained in one gallon of gasoline, 76,000 BTU/gal versus 114,330 BTU/gal, respectively. This would result in an ethanol vehicle requiring 1.5 gallons of ethanol for every 1 gallon of gasoline in a gasoline vehicle. However, like methanol, ethanol is superior in its energy efficiency to gasoline, which narrows the volume difference between ethanol and gasoline. Based on the similar chemical properties of ethanol and methanol shown below, I estimate ethanol to provide similar improvements in engine efficiency over gasoline as was determined for methanol: 2.5 percent more efficient for an E85 vehicle and 30 percent for a dedicated E100 vehicle.[1] The comparison of ethanol, methanol, and gasoline is shown in Table 2.

One of the efficiency improvements for the dedicated ethanol vehicle and the primary improvement for the FFV is due to the higher post-combustion pressure ethanol has compared to gasoline even in identical engines. The relative post-combustion pressures of ethanol and methanol can be investigated by comparing the increases that occur in gaseous moles during the combustion of gasoline, ethanol, and

Table 1

Plant Gate to Station Pump Costs
(cents per gallon)

	Typical Gasoline	M85	M100	E85	E100
Distribution	6(3)	3	3	3	3
Service Station Markup	9	6-8	5-7	6-8	7-9
All Taxes	24	14	12	17	16
Total Costs	39(36)	23-25	20-22	26-28	26-28
Gasoline Equiv Ratio	1.00	1.74	2.00	1.40	1.50
Total Costs, Gasoline Equiv	39(36)	40-44	40-44	36-39	39-42

Table 2

Fuel Properties

	Ethanol	Methanol	Gasoline
Lower Heating Value (BTU/gal)	76,000	57,000	115,000
Octane Rating ((R+M)/2)	98	99	87
Flammability Limits (vol%)	3.3-19	6.7-36	1.4-7.6
Density (lb/gal)	6.61	6.63	6.20
Flash Point (F)	55	52	-45
Heat of Vaporization (BTU/gal)	2,600	3,300	800
Gasoline Energy Equiv. Moles	3.38	6.54	1.00
Gaseous Reactants (stoi)	48.41	46.80	48.92
Gaseous Products (stoi)	55.17	56.61	52.17
% Gaseous Moles Increase (stoi)	13.97	20.95	6.64
% Gaseous Moles Increase (0.7)	9.78	14.67	4.65

methanol. The mole quantity of the fuel is not included in the reactant side since it is assumed that this fuel will in the most part remain a liquid until the majority of the compression stroke has occurred. So, although the alcohol fuels require more moles of fuel to provide an equivalent gasoline charge, the additional work required to compress the alcohol fuels is small and can be neglected.

During the stoichiometric combustion of gasoline, ethanol(E100), methanol(M100), the gaseous moles increase 6.64 percent, 13.97 percent, and 20.95 percent, respectively. The increase for ethanol is right in the middle between gasoline and methanol, so it should have half of the 6 percent efficiency improvement that was reported for methanol. This analysis falls in the range of testing results that have shown the increase to be between 3 and 4 percent.[2,3] Therefore, E100 is estimated to have a 3 percent efficiency improvement over gasoline due to its higher post-combustion pressure. For E85, the corresponding improvement is estimated at 2.5 percent.

The following two efficiency improvements apply only to the dedicated ethanol vehicle. First, the high octane rating of alcohol fuels allow a higher compression ratio of 13:1 compared to 9:1 for the gasoline engines, which will increase engine efficiency by about 10 percent for both methanol and ethanol.

Second, fuel conversion efficiency has been shown to follow a linear relationship with the fuel to air equivalence ratio when this ratio is below 1.0.[4] Since, theoretically, ethanol and methanol can maintain flammability at the same low equivalence ratios of about 0.52, we could assume that ethanol has the same efficiency benefit due to burning lean as methanol. This does not mean that we can expect these fuels to burn at these low ratios. Experience with ethanol has shown a minimum equivalence ratio of 0.7 for acceptable driveability.[5] Testing done by the EPA on dedicated methanol vehicles also produced a driveability of limit of around 0.7. The benefit for the lean burning ethanol engine, therefore, appears to be in the same range as the estimated benefit of 15 percent for methanol. Tests conducted in a single-cylinder engine with an equivalence ratio of 0.7 showed an improvement of about 12 percent in efficiency using ethanol compared to ethanol burning at stoichiometry.[3]

In regards to the lean-burn combustion, an interesting benefit, albeit small, of ethanol over methanol may be in the effect that the lean-burn combustion has on the post-combustion pressures of the two fuels. As the equivalence ratio decreases in the lean-burn range, the percentage increase in the moles of gaseous products during combustion also decreases. For ethanol, this decrease will be smaller than for methanol, and therefore will have a smaller reduction in its post-combustion pressure. Assuming the estimated improvement due to lean burn for methanol takes into account the decreasing effect it will have on the post-combustion benefit, we could assume that the ethanol lean-burn estimate should be slightly higher since the post combustion reduction is smaller. At an equivalence ratio of 0.7, the methanol post-combustion benefit is reduced by about 2 percent, while the ethanol post-combustion benefit is reduced by about 1 percent. Therefore, the ethanol lean burn efficiency improvement may be 1 percent greater than that of methanol lean-burn.

The increased power and efficiency of the ethanol engine could result in downsizing the engine to maintain equivalent performance to a gasoline engine. The reduction in engine weight, along with the reduction in vehicle frame weight due to the smaller engine, could provide an additional efficiency benefit. This is reduced partially, however, by the additional weight of the fuel due to the ethanol vehicle's larger fuel tank and the higher fuel density. The Methanol Special Report makes note of this weight reduction, but does not quantify an efficiency improvement. However, the graph of fuel efficiency improvements contained in that report indicates a total improvement of about 2.5 percent due to weight reduction and an efficiency reduction of about 1.5 percent due to the additional fuel weight of the methanol vehicle, which results in a total efficiency benefit of about 1.0 percent due to weight reductions for the methanol vehicle.

The ethanol vehicle should benefit from the same weight reductions, but will not have to carry as much fuel weight as the methanol vehicle. An efficient, dedicated methanol vehicle is estimated to require 1.54 gallons of methanol to travel the same distance as 1.0 gallon of gasoline in a gasoline vehicle, while an efficient, dedicated ethanol vehicle is estimated below to require 1.15 gallons of ethanol. Therefore, the ethanol vehicle requires only 28 percent of the additional fuel volume as the methanol vehicle does and, since their densities are about the same, the efficiency reduction of 1.5 percent due to the methanol fuel weight should be reduced by 72 percent for ethanol. The efficiency reduction associated with ethanol fuel weight should be a little under 0.5 percent, which results in a net benefit of about 2.0 percent due to weight reductions for the dedicated ethanol vehicle compared to 1.0 percent for the methanol vehicle.

Overall, summing the individual efficiency improvements of ethanol due to higher post-combustion pressure, higher compression ratio, and lean-burn ability results in a total improvement of 28 percent. The Methanol Report results in a total improvement for methanol of 31 percent. Taking into account the nature of these individual estimates and the range that must be assumed for them, I feel it is reasonable to estimate the total ethanol efficiency improvements at 30 percent as was done for methanol. This assumption is

strengthened by the slight efficiency improvements in ethanol over methanol due to the smaller fuel weight and the smaller post-combustion pressure losses for lean-burn operation, which were not been included in the above total.

Gasoline Equivalent Ethanol Retail Price:

The projected gasoline equivalent ethanol retail price can now be determined by multiplying the total retail price by the gasoline equivalent ratio as shown in Table 3. Assuming no efficiency improvements, ethanol has a ratio of 1.40 for a FFV using E85 and 1.50 for a dedicated vehicle using E100. For a FFV using E85, an energy efficiency benefit of 2.5 percent can be expected resulting in a ratio of 1.37 (1.40 divided by 1.025). A 30 percent efficiency improvement for a dedicated E100 vehicle results in a ratio of 1.15. Therefore, the gasoline equivalent retail price for E85 (2.5 percent improvement) would be $1.19 to $1.81. For E100, the gasoline equivalent retail price would be $1.29 to $2.07 for a vehicle with equal efficiency and $0.99 to $1.59 for a dedicated vehicle with 30 percent better efficiency.

VENCILE COST

A dedicated ethanol vehicle and a dedicated methanol vehicle should essentially be the same due to the similar properties of these alcohol fuels. Differences would exist in the fuel mixture and warming systems due to ethanol's lower RVP. Ethanol has been found to require either a stronger heat-up system than methanol or fuel additives to improve cold start and driveability.[5] The ethanol fuel system should be only a slight increase in cost, if any, compared to the methanol fuel system since the same design could be modified for either fuel. Also, the cold start problem may be solved by a different design such as propane assistance, which should cost the same regardless of the alcohol fuel used.

In addition, the ethanol fuel tank can be about 25 percent smaller than with methanol, which will provide a cost and space savings. Compared to gasoline vehicles, the ethanol tank would be 15 percent larger. As with methanol, the ethanol fuel tank may require safety devices such as flame arrestors due to the possibility of the flammability limits occurring in the tank since both fuels have similar flash points.

Following the same methodology as used for the methanol vehicle, the best estimate appears to be one of no cost increase for a dedicated ethanol vehicle compared to a gasoline vehicle. As with the methanol vehicle, this is a projection with a definite factor of uncertainty.

Table 3

Gasoline Equivalent Ethanol Retail Price
(cents per gallon)

	E85* 2.5% Better Efficiency	E85** 2.5% Better Efficiency	E100 Equal Efficiency	E100 30% Better Efficiency
Ethanol Plant Gate	85-128	85-128	100-150	100-150
Producer Subsidy	-34	-34	-40	-40
Gasoline Blending	10	16	0	0
Distribution, Markup, and Taxes	26-28	26-28	26-28	26-28
Total Ethanol Retail Price	87-132	93-138	86-138	86-138
Gasoline Equiv. Ratio	1.37	1.37	1.50	1.15
Total Gasoline Equiv. Ethanol Retail Price	119-181	127-189	129-207	99-159

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* Gasoline from low crude 68.6 cents/gallon.
** Gasoline from high crude 106.7 cents/gallon.

The same also holds for the ethanol FFV. As with the methanol FFV, the major cost differential compared to a gasoline vehicle is the fuel sensor. There should be no major hardware differences between the two. Therefore, the ethanol FFV is also estimated to have the same $300 cost increase over a gasoline vehicle as the methanol FFV.

CONCLUSIONS

The data used in this analysis are limited. Primarily, the estimates and conclusions were arrived at by comparing the chemical properties of ethanol and methanol and not by actual test data. Therefore, the efficiency improvements estimated for ethanol should be taken along with the range that would accompany such an analysis.

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References

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5. "A Motor Vehicle Power Plant for Ethanol and Methanol Operation," In Third International Symposium on Alcohol Fuels, California, Menrad, H., California, May, 1979.

Appendix D

Memo Listing Ethanol Vehicle Programs

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR, MICHIGAN 48105

OFFICE OF
AIR AND RADIATION

APR 9 1990

MEMORANDUM

SUBJECT: Ethanol Fueled Vehicles - Experience to Date

FROM: Craig A. Harvey, Mechanical Engineer
Technical Support Staff
Craig A. Harvey

TO: Charles L. Gray, Jr., Director
Emission Control Technology Division

THRU: Phil Lorang, Chief
Technical Support Staff

Following is a list I recently compiled of sixteen neat and near neat ethanol vehicle programs that have been conducted or are now being conducted. These programs range from tests of a single vehicle up to the large in-use ethanol-fueled fleet that now makes up most of Brazil's motor vehicle population. Each entry consists of a narrative summary of the vehicle(s) involved in the program, the fuel(s) used, what sort of measurements were done if any, a summary of results, and the appropriate reference(s).

1. Brazil: In-Use Fleet

Since 1983 90-95% of all passenger vehicle sales have been dedicated neat ethanol vehicles. In 1985 alone, about half a million of these vehicles were sold. These vehicles have been operated on hydrous ethanol with 0-5% gasoline (possibly more gasoline recently due only to an ethanol shortage in Brazil). They are equipped with a separate gasoline tank to automatically provide a small amount of gasoline for start-up only if the ambient temperature is below about 40°F. The compression ratios are up around 12:1 to take advantage of ethanol's high octane (it is law that an ethanol vehicle must achieve 75% of the fuel economy of the equivalent gasoline vehicle).

> "Transportation Fuels Policy Issues and Options: The Case of Ethanol Fuels in Brazil," Sergio C. Trindade, presented at the conference on "Alternative Transportation Fuels in the 1990's and Beyond," Asilomar, California, July 1988.

"Brazilian Vehicle Calibration for Ethanol Fuels," G. E. Chui, et al, Ford, Third International Symposium on Alcohol Fuels, Asilomar, California, May 1979.

"Phase Separation and Cold Start Devices for Neat Ethanol Vehicles, The Brazilian Experience," letter from Plinio Nastari, Ethanol Trade, S.A./SOPRAL, to Eric Vaughn, Renewable Fuels Association, December 21, 1989.

(Additional Brazil program references are listed below)

2. Ford Brazil, 4th International Symposium

Two Brazilian neat ethanol vehicles were tested for fuel economy, performance, material compatibility, and durability. One vehicle was a carbureted 1.6 L Corcel II, with a 12.0:1 compression ratio. The second was a carbureted 5.0 L Landau with an 11.0:1 compression ratio. Both vehicles were equipped with a secondary gasoline low temperature cold-start system.

No emission measurements were done, but based on the fuel economy testing it was concluded that, if fully optimized for ethanol operation, ethanol vehicles have the potential to achieve fuel economy 90-95% that of gasoline vehicles on a straight miles per gallon basis (not gasoline equivalent mpg). Since the energy content of ethanol is only 2/3 that of gasoline, this corresponds to an energy efficiency almost 30% greater than comparable gasoline vehicles.

"Aspects of the Design, Development and Production of Ethanol Powered Passenger Car Engines," F. B. P. Pinto, IV International Symposium on Alcohol Fuels, May 21-25, 1984.

3. Brazil, SAE 850390, Szwarc/Branco

Eight Brazilian neat ethanol vehicles and six gasoline vehicles were emission tested on the FTP (the gasoline contained 5% ethanol). The ethanol vehicles averaged 1.98 g/mile HC (FID), 23.1 g/mile CO, 2.08 g/mile NOx, and 253 mg/mile aldehydes. The gasoline vehicles averaged 6.29 g/mile HC (FID), 67.1 g/mile CO, 1.83 g/mile NOx, and 47 mg/mile aldehydes. Total aldehydes were measured using the MBTH procedure. These Brazilian vehicles were not equipped with any sort of catalytic converter.

"Automotive Use of Alcohol in Brazil and Air Pollution Related Aspects," A. Szwarc and G.M. Branco, CETESB, SAE Paper 850390, 1985.

4. GM Brazil, Baumgartl, 1984

Seven Brazilian ethanol vehicles were compared to their gasoline fueled counterparts for fuel consumption and emissions. These vehicles were all carbureted and had no catalytic converter. The fuel consumption of the ethanol vehicles on a L/100km basis ranged from 19-40% greater than the gasoline vehicles. Emissions were tested on a hot FTP driving cycle. The ethanol vehicles averaged 3.9 g/mile HC (FID), 41.0 g/mile CO, 3.1 g/mile NOx, 146 mg/mile formaldehyde, and 519 mg/mile acetaldehyde. The gasoline vehicles averaged 10.6 g/mile HC, 84.0 g/mile CO, and 4.1 g/mile NOx. No aldehyde measurements were taken for the gasoline vehicles.

"Energy Produced by Liquid Fuels of Regenerative Sources Taking as Model the Brazilian Ethanol Program," Paul Baumgartl, General Motors do Brasil, presented at the Hannover Fair "Technologies for Objective Energy Utilization," April 1984.

5. VW Brazil, "A Study of Hydrocarbon Composition...", 8th International Symposium.

Exhaust from a single Brazilian ethanol 1.8 L 1987 VW Santana Quantum was measured with a GC to determine the fractions of various HC components. The vehicle was carbureted, had a compression ratio of 12.3:1, and was fueled with hydrous ethanol (93.2%). The total HC consisted of 9.1% non-oxygenated HC, 2.8% acetaldehyde, and 88.1% unburned ethanol. Methane comprised about 30% of the non-oxygenated HC. On a g/km basis, the vehicle emitted 0.546 g/km non-oxygenated HC, and 2.165 g/km acetaldehyde plus ethanol.

"A Study of Hydrocarbon Composition Emitted by Straight Ethanol-Fueled Vehicles," H. Joseph, R. Siekmann, G. Pischinger, 8th International Symposium on Alcohol Fuels, November 1988.

6. VW Brazil, 2nd International Symposium.

A 1.6L carbureted gasoline vehicle was modified in two steps to run on neat ethanol. Effects on driveability, fuel economy, and durability were reported, but no emission measurements were done. The first step retained the original 7.2:1 compression ratio, but in step 2 it was raised to 11.1:1, which yielded energy savings up to 30% over the base gsaoline configuration.

"The Use of Ethanol from Biomass as an Alternative Fuel in Brazil," H. Hertland, H. W. Czaschke, and N. Pinto, II International Symposium on Alcohol Fuels, 1977.

7. California Energy Commission - Fleet 1

Four 1980 Ford Pintos were retrofitted to operate on neat anhydrous ethanol denatured with 2-5% unleaded gasoline. For comparison, four unmodified gasoline fueled Pintos (and four Pintos modified for methanol use) were operated in the same fleet. All these vehicles had carburetors and 3-way catalyst systems. Two of the ethanol vehicles had their compression ratio increased from 9:1 to 12:1.

The only emission results reported for these vehicles were total aldehyde emissions (MBTH method) of 10-40 mg/mile, which were described as being comparable to the gasoline vehicles.

"California's Alcohol Fleet Program, 1982 Progress Report for Senate Bill 620, California Energy Commission, December 1982. (also see next reference with final results from fleets 1 and 2)

8. California Energy Commission - Fleet 2

Twenty fuel injected VW Rabbits with 3-way catalyst systems were optimized by a contractor (AES) in coordination with VW to operate on neat ethanol denatured with 2-5% unleaded gasoline. These compression ratio of these vehicles was increased to 12.5:1. Only one baseline gasoline vehicle was used in this fleet, along with nineteen methanol vehicles.

Eight of the twenty ethanol vehicles were tested for emissions. Various configurations (e.g., EGR rates) were tried in order to minimize NOx emissions. In the best NOx configuration, emissions averaged 0.38 g/mile HC (total FID), 5.36 g/mile CO, and 0.26 g/mile NOx. In other configurations 8-vehicle average emissions ranged from 0.27-0.45 g/mile HC, 1.17-1.81 g/mile CO, and 0.36-0.53 g/mile NOx. Total aldehydes ranged from 18-146 mg/mile by the MBTH method.

"California's Alcohol Fleet Test Program-Final Results," F. J. Wiens, M. C. McCormack, R. J. Ernst, R. L. Morris, and R. J. Nichols, VI International Symposium on Alcohol Fuels, May 21-25, 1984.

9. Alcohol Energy Systems -- VW Ethanol Concept Vehicles

Two vehicles are mentioned in this study -- a Rabbit (mileage 200-1100) similar to those used in the above CEC Fleet 2, plus a VW Jetta. The Rabbit was equipped with a separate gasoline cold temperature starting system, 12.5:1 compression ratio, fuel injection and 3-way catalyst system. The mileage on the Rabbit ranged from 200-1100 during this program, while the Jetta had about 1500 miles on the odometer.

Exhaust emissions from the Rabbit were measured at 0.201 g/mile HC (FID), 0.94 g/mile CO, and 0.57 g/mile NOx. Emissions from the Jetta were 0.302 g/mile HC, 1.52 g/mile CO, and 0.286 g/mile NOx. SHED evaporative emissions were measured from the Rabbit and found to be less than 2.0 g/test (FID) despite the separate cold-start gasoline system.

"Report on the Rabbit Concept Vehicle for Neat Ethanol Operation," submitted to Alcohol Energy Systems Incorporated by Volkswagen of America, Inc., pursuant to the Contract of April, 1981.

10. Santa Clara, Baisley/Edwards, 4th International Symposium

Five 1978 Ford Pintos were retrofitted to operate on neat ethanol (denaturant formula CD-19, 100 parts ethanol, 4 parts methyl isobutyl ketone, 1 part hydrocarbon). These vehicles were carbureted and were standardly equipped with an oxidation catalyst and no EGR. An electric manifold heater was added that allowed cold starts down to 32°F. These vehicles were operated for (or already had) about 10,000 miles each.

One of these vehicles underwent emission testing, and 4-test averages showed 0.71 g/mile HC (as carbon), 5.27 g/mile CO, and 1.83 g/mile NOx. When operated on gasoline, a similar (the same?) car had 0.38 g/mile HC (as carbon), 2.06 g/mile CO, and 5.55 g/mile NOx. The ethanol vehicle was calibrated fairly rich to help driveability.

"Emission and Wear Characteristics of an Alcohol Fueled Fleet Using Feedback Carburetion and Three-Way Catalysts," W. H. Baisley, C. F. Edwards, IV International Symposium on Alcohol Fuels, May 21-25, 1984.

11. Nebraska State Patrol - 1981 paper by William Scheller

Two carbureted MY 1979 Chevrolet Impalas equipped with 350 CID V-8 engines and propane cold starting systems were operated by the Nebraska State Patrol for over 20,000 miles each. One vehicle had a compression ratio of 8.1:1 and was operated for 34,000 miles on neat ethanol, while the other had a compression ratio of 10.0:1 and was operated on ethanol for about 21,000 miles. No further data was provided.

Paper documenting the use of neat ethanol in two 1979 Nebraska State Patrol vehicles, Dr. William A. Scheller, University of Nebraska, 1981.

12. Nebraska - Dedicated E85 vehicle, summer 1989

A gasoline car was retrofitted to operate normally on E85. This is the car driven by President Bush during his visit to Lincoln Nebraska in June of 1989. Due to limited availability of E85 refueling facilities in the use area of the vehicle, it was later re-configured to operate on gasoline instead of ethanol.

13. Ford Canada

In June 1987 Ford delivered two Crown Victoria FFV's to St. Lawrence Starch to be used with E85 in a long duration program of at least 60,000 miles. Testing proved cold start capability with this fuel at -20°F in under 5 seconds. These vehicles have a 9:1 compression ratio for compatibility with gasoline fueling if necessary.

Prior to delivery, these two vehicles plus another similar FFV were tested by Ford on E85. FTP test results showed 0.17-0.30 g/mile HC (total FID), 0.58-0.72 g/mile CO, and 0.53-0.68 g/mile NOx.

> Research/Demonstration Program for Flexible Fuel Vehicle, Fourth Quarterly Review, Ford of Canada / Ford Research, June 24, 1987.

14. "The Development of Carburettor Systems..." Gavin, Kemp, Dryer, 4th International Symposium.

A Toyota Corolla that had been retrofitted to be a dedicated M85 vehicle with a 10.6:1 compression ratio was fueled with hydrous ethanol to test for driveability and performance compared to methanol. Due to the lack of any special cold start system, the vehicle was started on M85 and then switched to ethanol operation after being warmed up.

No quantitative measurements were reported, but it was shown that the vehicle would operate satisfactorily on ethanol given the above starting procedure.

> "The Development of Carburettor Systems For The Use of Alcohol in Spark Ignition Engines," M. Galvin, R. Kemp, F. Dryer, IV International Symposium on Alcohol Fuels, May 21-25, 1984.

15. Bechtold/Pullman, 3rd International Symposium.

A carbureted 1976 Chrysler vehicle with a 318 CID V-8 engine at a compression ratio of 8.5:1 with EGR was tested on the FTP for emissions with and without an oxidation catalyst. A special fuel induction system including more complete water jacketing was used to provide better fuel vaporization and a more consistent fuel:air ratio to all the cylinders. Fuels tested were summer grade gasoline, methanol, and neat ethanol denatured with 4.5% methanol/0.9% ethyl acetate/4.5% methyl iso-butyl ketone. Each fuel was tested with the catalyst installed at fuel:air equivalence ratios of 0.8 (lean), and 1.0 (stoichiometric). Without the catalyst a test point at an equivalence ratio of 1.2 (rich) was included. The same electronic spark timing program was used for all tests. The focus of the study was on evaluating the fuels under conditions of equal stoichiometry and fuel preparation rather than attempting optimization for any of the fuels.

Emissions measured included total aldehydes (by MBTH?), unburned fuel reported as FID measured carbon (adjusted for differing mass per carbon and FID response for the alcohols), CO, and NOx. With the catalyst the results were 203 mg/mile aldehydes, 1.1 g/mile FID carbon, 9 g/mile CO, and 0.35 g/mile NOx. Without any catalyst there were 600-1800 mg/mile aldehydes, 2.0-5.5 g/mile FID carbon, 11-20 g/mile CO, and 0.5-0.8 g/mile NOx.

"Driving Cycle Comparisons of Energy Economies and Emissions from Alcohol and Gasoline Fueled Vehicles," Richard Bechtold and Barrett Pullman, III International Symposium on Alcohol Fuels, May 28-31, 1979.

16. South Dakota Corn Growers Association E85 Corsica

A 1988 2.0 liter TBI Chevrolet Corsica was modified to run on ethanol-gasoline mixtures ranging from straight gasoline to 85% ethanol. Prior to modification the vehicle had 43,000 miles on the odometer, and approximately 3000 miles have been added since the modification. The modification consisted of (a) installation of the Webster-Heise valve to improve fuel vaporization, (b) reprogramming the on-board computer, and (c) addition of an auxilliary 12 gallon fuel tank solely for comparison tests. No fuel sensor (as used in current FFV's) was added. The conversion package cost $2,000, but a commercially produced package (without need for the auxilliary tank) was estimated to cost about $300.

FTP and HFET (highway fuel economy test) data were collected at the Environmental Testing Corporation (ETC) in Denver, and further data are being collected by the California RFA at the ACS Laboratories in Ontario, California. The E85 fuel being used consists of 85% pure ethanol and 15% unleaded gasoline (RVP not reported). The Denver FTP data show base gasoline emissions of 0.19 g/mile HC (presumed to be total FID), 2.40 g/mile CO, and 8.11 g/mile NOx (NOTE: NOx was measured prior to the catalyst as raw engine-out emissions). The corresponding E85 emissions were 0.142 g/mile HC, 1.83 g/mile CO, and 7.87 g/mile NOx. CO_2 was also measured and decreased by about 4.6%. HFET emissions of HC and CO were much lower than the FTP, and NOx emissions were greater, but all three pollutants had greater percentage reductions relative to gasoline than on the FTP.

Letter and attachments from Dan Iseminger, Administrator, South Dakota Corn Utilization Council, to William Reilly, Administrator, EPA, March 23, 1990.

(End of list)